

The Impact of Post-Earthquake Fire on the Urban Environment

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**Fire Engineering Research Report 98/1
June 1998**

This report was presented as a project report
as part of the M.E. (Fire) degree at the University of Canterbury

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ABSTRACT

Major earthquakes are rare events in most countries but there have been cases in urban regions of fire following earthquakes. Its potential for growth and spread was again evident in the recent Northridge and Kobe earthquakes.

This report identifies ways in which fire protection and fire engineering can work through public sector and private sector actions to reduce post-earthquake fire losses in urban building stock. It suggests a set of practical measures for building fire loss reduction that could be taken by territorial authorities, Fire Service, building owners and tenants, property and risk managers, insurers and fire engineers.

It presents analyses of literature from international sources concerning fourteen recent earthquake events having fire impacts on major population centres. They identify the exceptional conditions present in the post-earthquake environment after major shaking, and how the mechanisms of fire ignition and the dynamics of fire spread usually present in the non-earthquake situation are modified in the aftermath of an earthquake to escalate fire losses, and cause the impairment of the normal processes for the control and suppression of fire.

The management of the impact of fire in buildings can be achieved through structural fire design, to control the movement of fire and to provide structural stability. However, the structural and non-structural damage caused to buildings by earthquakes can lead to the loss of integrity of passive protection systems and allow the uncontrolled migration of smoke and hot gases internally. If automatic or manual suppression is delayed, the fire resistance of structural members is likely to be challenged.

Fire protection and earthquake protection need to interact if fire safety systems are to continue to function after an earthquake. Effective seismic capacity in the design of sprinkler system components, pipework and on-site water storage are essential for reliable performance in the aftermath of a major earthquake, as the response of fire brigades to requests for emergency assistance, and their suppression effectiveness at firegrounds are likely to be impaired.

This report provides a comprehensive list of measures for building fire loss reduction in the aftermath of an earthquake, and recommends areas for future research.

ACKNOWLEDGEMENTS

Dr. Andy Buchanan - for helpful guidance and patient supervision throughout.

Dr. Charley Fleischmann - for suggestions on project topic and getting me started in the research mode.

Pat Roddick and Christine McKee in the Engineering Library - for very helpful assistance with data base searching, and interloan and international document delivery.

Professional engineering colleague Brent Jones - for practical support in keeping my over-burdened home computer going for the duration of the project.

Paul Beaumont and Nigel Allott, Fire Engineers - for helpful discussion.

Telecom New Zealand Limited - for financial support to undertake the course.

My Family - for tolerating my numerous absences from family activities while “the writing was being done”, and for encouragement.

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CHAPTER 1.0

INTRODUCTION

1.1 Background

1.1.1

Major earthquakes are rare events in most countries but there have been cases in urban regions of fires following earthquakes. The effectiveness of fire protection systems and fire-fighting efforts can be severely impaired at those times. The following events, evidenced over the last ninety years in at least eleven disasters were the consequences of such impairments. These events are generally renowned for the severity and magnitude of the fires following major earthquake shaking:

- San Francisco (1906)
- Tokyo (1923)
- Hawkes Bay, New Zealand (1931)
- San Fernando Valley, Los Angeles County (1971)
- Managua, Nicaragua (1972)
- Mexico City (1985)
- Whittier Narrows, Los Angeles County (1987)
- Loma Prieta, San Francisco (1989)
- Hokkaido Nansei-oki, Japan (1993)
- Northridge, Los Angeles County (1994)
- Kobe, Japan (1995)

1.1.2

The problem of fire spread and especially conflagration in urban regions following earthquake had been regarded very seriously in Japan at least over the last three decades, but not until much more recently in the United States. The Proceedings of a joint US-Japan Workshop on Urban Earthquake Hazard Reduction held in July 1984 at Stanford University, California, and reported by Scawthon in EERI (1985), acknowledged that the problem of post-earthquake fire had been largely ignored in US until that time, in spite of the fact that in US, as well as in Japan, the single most damaging natural events of the twentieth century had been fire following earthquake: namely the San Francisco 1906 and Tokyo 1923 events.

The reason as suggested by Scawthon for the US attitude to post-earthquake fire was the relatively low-key attitude in the US about seismic risk in general. However, he had noted that in Japan earthquakes were feared not only for post-earthquake fire but also equally for shaking, tsunami, liquefaction and landslide damage.

While many aspects of earthquakes and the damage they cause have been investigated in recent years, Scawthon et al (1988) acknowledged that little research had been reported in the US on fires following earthquakes in urban areas. However, the potential for catastrophe in terms of losses of life and property has been re-emphasised dramatically in the most recent Northridge and Kobe earthquakes. These events have also increased activity in the US towards assessing what needs to be achieved in research and technology development to reduce the losses from future post-earthquake fires.

In NIST 889 (1995) Chung et al reported the proceedings of the post-earthquake fire and lifelines workshop held in January 1995 at Long Beach, California. He identified further research and development needs falling into the two categories of ignition and fire spread, and fire control.

In New Zealand a study of urban property losses due to post-earthquake fire has been reported in Cousins et al (1990). This was an assessment by W.J.Cousins, D.J.Dowrick, S.Sritharan (then of the DSIR Physical Sciences, Lower Hutt), and others, of the urban property loss due to post-earthquake fire resulting from the Wellington fault event. The same event was used by D.Hopkins in 1995 for his assessment of the cost of consequential fire losses and of the repair cost for earthquake-damaged buildings and infrastructure. That was reported in Hopkins (1995).

1.2 Purpose of this project

1.2.1

The purpose of this project is to identify the impact of fire on the built urban environment after a major earthquake and to suggest ways in which fire protection and fire engineering can be used through public and private sector actions to reduce fire losses.

An essential feature of the project is an analysis of fires following fourteen major earthquake events to identify the critical issues driving post-earthquake fire impacts. Although fire was not a consequence of the 1987 Edgecumbe, New Zealand earthquake, that event is also reviewed to establish in particular the extent of the well reported damage to sprinkler systems and water supplies.

As a basis for comparison with post-earthquake conditions consideration is given to the dynamics of fire behaviour in buildings and the effects of passive and active measures for fire control under normal conditions, and the range of responses available to building fire risk.

The performance requirements of some current codes are also described to establish generally the range of fire and loss control measures mandated by code for the urban post-earthquake fire situation.

1.2.2

Described in more detail, this project considers:

1. The dynamics of fire growth, development, and spread within and beyond the fire building to establish a basis for identifying how fire protection in the built urban environment is changed in the aftermath of a major earthquake. It is evident that the extent a fire is permitted to follow natural growth and development patterns to the stage of uncontrolled destruction of the fire building is almost entirely influenced by
 - those inbuilt fire protection measures both passive and active
 - effectiveness of any manual fire-fighting measures which may be applied at the fireground.

In the aftermath of a major earthquake these factors are critical to the extent of the resulting fire damage within individual buildings, and over wider urban areas.

2. A systematic approach to fire safety and a response to building fire risk, presented in terms of the management of fire impact through structural fire design, and drawing on the results of an analysis of the post-earthquake fire impacts on the built urban environment of fourteen major earthquake events, to discuss:

- nature of ignition sources
- mechanisms of fire spread (including urban conflagration)
- condition of fire safety systems
- effects of major earthquake shaking on public water supply systems and the influence on fire-fighting tactics.

1.3 Fire Safety Goals

1.3.1

This report recognises life safety, property protection, business protection and environment protection as goals of fire safety in the urban built environment.

Traditionally building codes have addressed building fire safety from the point of view of protection of the building and its contents. However, Beck (1989) noted that generally today's building codes focus on the safety of the building's occupants.

BIA (1992) in C3/AS1 Section 1.0 acknowledges that priority is given to life safety, and less emphasis is applied to property protection in the New Zealand Building Code than in NZS 1900: Chapter 5 (now obsolete), but noted that inevitably the two subjects overlap.

With reference to BIA (1992) the main fire safety objectives within the Code are for:

1. Safeguarding people from injury or illness from a fire.
2. Facilitating Fire Service operations.
3. Protecting adjacent property from the effects of fire.
4. Safeguarding the environment from adverse effects of fire.

In terms of the extent that protection should be provided to adjacent property from the effects of fire, precautions apply only to parts of a building which if collapse occurred would cause damage across a relevant boundary, or damage to an adjacent household unit.

1.3.2

Buchanan (1995) noted that if protection of property, including the building structure and contents is considered necessary (by the owner or tenant, or the insurer of the building or contents), then the designer must establish any additional performance requirements beyond those required in Building Regulations (1992). The additional performance requirements may be, for example:

- contents of the building will not be seriously damaged
- building itself will not be seriously damaged
- damage to the building will be easily repairable.

1.4 What has been discovered by this project

The main issues are:

1. Building fire initiations following earthquakes

It is not possible to eliminate all initial fire outbreaks in buildings following a major earthquake, but the risk of these may be reduced by applying installation procedures to potential ignition sources to achieve effective restraint against shaking, and by applying fire preventative practices particularly in the area of the restoration of electricity and gas supplies after an earthquake.

2. Management of the impact of fire

The management of the impact of fire in buildings can be achieved through structural fire design, the intention of which is to control the movement of fire through containment or venting, and to provide structural stability through structural design, materials selection and installation.

Structural fire protection systems are not tested for earthquake movement, but they have to be tough enough to remain in place during large deformations in fire resistance tests, which means that they will have some ability to accommodate movement from earthquake. However, the structural and non-structural damage caused to buildings by earthquakes can lead to the loss of integrity of passive protection systems and allow the uncontrolled migration of smoke and hot gases beyond fire compartments. If automatic or manual suppression is delayed, the fire resistance of structural members is likely to be challenged if their passive protection systems are damaged.

3. Damage to active fire protection systems

Installed detection, alarm and suppression systems may also be disabled by structural and non-structural building damage or be unreliable following strong earthquake shaking, which may also cause water supply failure and power supply failure. This may result in ignitions being undetected for a long period of time and in large fires which are more difficult to extinguish, and in larger fire losses. Building sprinkler system vulnerability varies from building to building according to the availability of on-site stored water and back-up power for booster pumps.

4. Provision of seismic resistance in sprinkler systems

Fire protection and earthquake protection need to interact if fire safety systems are to continue to function after an earthquake. Effective seismic capacity in the design of sprinkler system components, pipework and on-site water storage, through adequate interpretation of NZS 4541:1996, are essential for reliable performance in the aftermath of a major earthquake.

5. Fire brigade post-earthquake fire response

Following a major earthquake, the response of fire brigades to requests for emergency assistance, and their suppression effectiveness at firegrounds are likely to be impaired. The likelihood of multiple simultaneous ignitions, impassable access routes and reduced or exhausted water supplies due to earthquake damage to underground water distribution systems are expected to be the predominant causes, giving fires the opportunity to grow and spread over large urban areas, increasing fire losses in building stock.

1.5 References

1.5.1

The references used in this text are called up in References. Other useful reading is noted following References.

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CHAPTER 2.0

THE INTERACTIONS BETWEEN FIRE AND THE BUILT URBAN ENVIRONMENT

2.1 Background

2.1.1

This chapter examines the interactions between fire and the built urban environment, and suggests some appropriate responses to building fire risk. As such, it attempts to set the basis for this report by providing a means by which to consider in Chapter 8 how the dynamics of fire in buildings are modified by earthquake effects.

2.2 Conditions for fire in buildings

2.2.1

Conditions required

The elements of heat, fuel and oxygen exist in varying combinations throughout any building, but the phenomenon of fire in buildings, and particularly the chemical process of combustion, requires specific conditions to be in place before combustion proceeds.

Patterson (1993) identified the necessary conditions as follows:

- there will have to be a source of ignition (applied heat) somewhere in the building
- following ignition there will have to be sufficient fuel to enable combustion
- then enough oxygen to sustain combustion.

The “fire load” of a building has been defined as the combustible materials of its construction together with its combustible contents. Patterson noted that although this is a representation of the latent energy available for fire, it is not a complete indication of the severity of a potential fire. The rate at which fire will progress, and the rate at which heat is released is dependent on a more comprehensive set of conditions which Paterson has identified as:

1. Fire load ie. the nature of the fuel and the amount of fuel.
2. Arrangement of the fuel.
3. Size and shape of the room or compartment containing the fire.
4. Area and shape of the windows, and other openings.
5. Thermal insulation of the walls and ceiling.

Conditions 1 and 2 relate principally to the combustible contents of a building, while the conditions 3, 4 and 5 relate to building design.

The term “fire severity” has been defined in Butcher and Parnell (1983) as “the condition of a fire in a building which relates to the maximum temperature reached and to the duration of burning”. When defined in this way fire severity is the potential which fire has to destroy or damage the building, the contents, and adjacent property.

2.2.2

Factors affecting fire severity

According to Butcher and Parnell all of the conditions 1 - 5 above determine the fire severity, but more specifically, and with reference to their definition of fire severity:

- the maximum temperature reached is determined by the rate of burning of the fuel
- the time the maximum temperature persists is determined by the duration of burning of the fuel.

The rate, and the duration, of burning of the fuel in turn depend on all of the conditions as previously identified in Patterson (1993), but with further explanation being given in the following:

- the nature, amount and arrangement of the fuel
 - the product of the calorific value (MJ/m^3) of the fuel and the amount of fuel in volume terms (m^3) indicates the maximum quantity of heat released if all of the fuel is consumed
 - the arrangement of the fuel in terms of the separation between combustibles, and the height of combustibles, influence the speed of fire spread (tall items allow flames to reach the ceiling sooner, and can promote the rapid sideways movement of flames under a ceiling, fire spread to other items, and to combustible wall linings and hangings)
 - the amount of exposed surface area of the fuel also influences the burning rate of the material
- the size and shape of the room containing the fire
 - room size influences the total amount of fuel available for combustion
 - room depth in relation to windows affects fire temperatures because the cooling air flow into and out of a deep room is less able to affect all burning material than in a shallow room
- the area and shape of windows
 - the area of the windows directly influences the amount of air reaching a fire and consequently its burn rate (and the transition from ventilation-controlled to fuel-controlled burning at a greater burn rate when glazing breaks)
 - in the ventilation controlled phase the burn rate of a fire is influenced by the ventilation factor $A\sqrt{H}$ which indicates that window shape is important (for windows of equivalent area, a tall narrow window will induce a higher burn rate than a wide squat window)
 - once fuel-controlled burning is established any increase in air supply acts to cool the fire by flame and smoke plume entrainment
- the extent that heat is retained within the fire compartment by the thermal insulating properties of the walls and ceiling
 - walls and ceilings of low thermal conductivity will conduct less heat from the fire, allowing it to reach a high temperature quickly, and will re-radiate heat to other combustible materials.

2.2.3

Fire temperatures

The temperature course of a fire in an enclosure may be divided into three periods, as noted by Lie (1995):

1. Growth period.
2. Fully developed burning period.
3. Fire decay period.

According to Lie, during the growth period heat produced by the burning materials is accumulated in the enclosure, and as a result other materials may be heated so severely that they also ignite. As the growth period progresses the gas temperatures rise very quickly and materials in all parts of the room ignite (at about 600°C) due to the well-known phenomenon of flashover. After flashover, the fully developed period starts and temperatures of about 1000°C or higher can be reached. During the decay stage the temperature falls at a rate depending on fuel-related factors, and on external factors eg fire suppression activities.

The transition of a fire from gradual fire growth to dramatic fire growth, as characterised by flashover, can only occur in compartment fires. According to Drysdale (1986), what is distinctive about compartment fires as compared to fires in the open is the effect of the heat containment caused by the presence of a roof or ceiling. Whereas, the heat from a fire in the open is convected and lost to the atmosphere, the heat from a contained fire spreads laterally below the ceiling and re-radiates into the compartment to increase the radiant flux at low level and the temperature of the fire and that of adjacent combustibles, which release flammable vapours and other combustible constituents. Flashover is the combustion of all these constituents. However, in very long or deep compartments it may be physically impossible for all the fuel to become involved at the same time.

Drysdale has noted that the external evidence of a post-flashover fire is heavy flame issuing from openings of the fire compartment (indicating the burning of volatile combustible constituents external to the room of fire origin).

2.3 Fire spread

2.3.1

Fire spread within buildings

Fire spread in buildings through openings, barriers and vertical routes was explained by Nutt (1996). This is summarised in the following:

Openings

- fire may spread from an enclosure to an adjoining enclosure through planned openings in its boundaries eg. closures such as doors which are in the open position
- fire may spread to an adjoining enclosure due to the failure of barriers and creation of unplanned openings in the enclosure due to structural collapse and/or cracks or

fissures eg. openings resulting from loss of integrity of the barrier such as walls, floors, and closures in the closed position

- fire may spread to an adjoining enclosure due to openings, from failure at penetrations of building services due to penetrations being either inadequately or not firestopped, or due to breached services eg due to the collapse of steel air-conditioning ducting as the result of its exposure to fire heat, thus allowing a hole to develop in the barrier
- fire spread beyond the fire enclosure occurs when one or more objects outside its enclosure boundaries ignite and burn, with the mode of ignition being either piloted or non-piloted
- piloted ignition occurs through direct flame impingement due to the burning of the hot gases which escape through the opening, or by flying brands from the fire enclosure if the fire grows in intensity and the exchange of flow through the opening becomes more vigorous
- fire may also spread along extended surface materials such as carpets, wall linings and ceiling linings
- radiant heat flux through one or more openings of the fire enclosure is the dominant means of fire spread by non-piloted ignition, and causes objects to ignite when the heat flux imposed on them is sufficiently high and sustained. Butcher & Parnell (1983) gave the incident intensity of radiation for the spontaneous ignition of wood as 12.6 kW/m^2 after 20 minutes of exposure to radiation assuming the worst condition of a room with one whole side occupied by window and the glazing destroyed by the heat very early in the fire.
- if the adjoining space is an enclosure, hot gases which escape from the fire enclosure will accumulate beneath the ceiling of the adjoining enclosure and contribute to the imposed radiant heat flux on the objects.

Barriers

- fires are, in general, only likely to spread through paths created by openings in the boundaries of the fire enclosure, hence fire spread through a barrier is only likely to occur when the barrier fails and develops one or more openings
- barriers which comprise internal walls or partitions are generally not designed to withstand severe fire (unless they are intended to protect a safe egress path), but they have an inherent fire resistance and are effective in preventing the spread of fire because of their capacity to shield potential combustibles against exposure to the effects of the fire, and can adequately limit the spread of fire during the early growth stage.

Vertical routes

- fires may spread vertically in a building through internal and external routes
- internal routes can be provided by continuous vertical spaces such as service ducts, lift shafts and stairwells, and construction openings if not fire-stopped
- spaces such as ceiling voids, spaces within hollow construction, under floors and under exterior cladding often provide access to a large number of connecting enclosures and have the potential to enhance the ventilation conditions of the fire and to allow the spread of smoke to remote enclosures undetected, and have the potential to pre-heat the internal spaces such that any combustible within these spaces will ignite more readily when there is sufficient heat or ventilation to do so
- fire may spread to the next floor via flames which project through external openings such as those resulting from breakage of glazed openings, and radiate back through the windows above.

2.3.2

Fire spread via the outside of the building

The mechanism of flame spread to other parts of the same building via the outside of the building, and the trajectory of these flames, was described by Butcher and Parnell :

- flames emerging from windows ignite combustible materials which are close to windows on the floor above the original fire floor
- a fire on the floor above develops until flames from this floor cause a fire on the next floor, and so on right up the building
- flame shape, and the shape of the flame trajectory, depend to a great extent on both the geometry of the building in which the window is situated and on the shape of the window. Width in relation to height controls the distance of the flames from the face of the building. Flames emerging from a window will tend to hug the face of the building when the window is wide in comparison to height and may, in some circumstances, actually be sucked into open windows.

2.3.3

Fire spread between buildings

Beyond fire spread within one building is the spread of fire from one building to another. The mechanisms of fire spread are similar, and these have been placed in context by Mehaffy and Richardson (1994) as:

- radiant ignition of the combustible exterior features of an adjacent building
- radiant ignition of combustible contents through windows of an adjacent building
- by fire brands, causing spot ignitions of building(s) down wind of the main fire.

According to Butcher and Parnell the transfer of heat by convection, by way of the hot gases and flames emerging from the burning building, is also a cause of fire spread between buildings but is relatively limited in range.

Kenna (1975) noted that the transfer of heat by radiation is normally the more severe condition.

The escape of flames and hot gases from a burning building by way of the windows, or out of the collapsed roof, has been noted by Butcher and Parnell and is summarised as follows:

- those out of the roof will go straight up, unless deflected by the wind, but even so, they are unlikely to impinge directly on to adjacent buildings
- flames out of windows will spread sideways as well as upwards but the extent of sideways spread is limited (being rather less than the height of the window).

They concluded that fire spread by direct impingement of flames or hot gases from a burning building can only occur when buildings are separated by a metre or two and then only if combustible material is present at, or on, the face of the exposed building.

Mehaffy & Richardson considered that the situation of fire spread between buildings is further compromised if structures are located in close proximity to one another and / or combustible waste and shrubs are permitted to accumulate between structures.

Towns which have closely spaced buildings, narrow streets and few green belts represent high fire risks, according to Kenna. If water supplies fail there is little that can be done to prevent spread of fire other than to provide fire breaks by using explosives, or heavy machinery, to demolish sound buildings.

Cousins et al (1990) also suggested the factors affecting fire spread between buildings should include:

- building density or proximity of buildings, and types and materials of building construction (these all affect the extent of exposure risk)
- topography of the surrounding area (in areas of urban development where housing is sited vertically close together in steep hill suburbs the exposure risk from a combination of radiated and convected heat transfer is higher)
- wind speeds and wind direction affect fire losses due to branding
- vegetation and its condition (the significance of vegetation in aiding fire spread is specific to the site, the species of vegetation, and the climatic conditions which define the vegetation's current state of combustibility).
- response of the fire brigade (including the availability of fire-fighting water at the site, and fire-fighting tactics) will influence the final fire size and the potential for fire spread.

A scenario for fire spread between adjacent high-rise buildings in dense concentrations, typical of CBD areas of major cities has been described in Scawthorn (1992). This scenario predicted the ignition of a high-rise building from the effects of a plume of smoke and hot gases rising from a nearby fire (even if from a fire in a low-rise building).

A worst case scenario (akin to a forest "crown" fire) was also predicted where there is no active exposure protection by the fire brigade, and where the ignition of upper floors proceeds from one high-rise to another. The process could be compounded by the fall of burning debris from an involved high-rise, onto the roofs, skylights and other portions of intervening lower buildings, igniting them and their fire spreading to the next high-rise (this of course is predicted on the basis of the virtual absence of effective fire suppression activities by the fire brigade).

2.4 Damage levels

2.4.1

The effects of fire

The effects of fire in a building are likely to be evident in two major ways. According to Patterson (1993) these are:

- the products of combustion, which are most evident in the smoke produced
- the heat generated and its effect on materials.

Smoke is generally the first evidence of fire, and indeed the only evidence which may appear in areas of the building remote from the fire. In relation to the products of combustion, the type, corrosivity and toxicity of the smoke are a direct result of the materials under combustion. These can be controlled to various extents at the design stage, through material selection.

The effect of fire heat on materials is particularly relevant to the building's structural components, which are frequently protected by insulative methods. Paterson noted that although insulative systems may still be in place after fire extinguishment, the effects of heat can have serious consequences on structural integrity.

2.4.2

Thermal properties of structural members

The ability of a material to handle exposure to high temperatures varies widely, and the thermal expansion of building materials, and the manner in which they conduct or dissipate heat, was noted by Patterson to be of extreme importance to the performance of construction assemblies under fire.

Thermal inertia (the product of thermal conductivity, density and specific heat) is an important quantity for determining the temperature which a surface will reach. The greater the thermal inertia, the higher the surface temperature reached in a fire.

Thermal diffusivity (the quotient of conductivity, and the product of density and specific heat) is important for indicating how fast a building material will heat up in a fire, and how rapidly the structure would absorb heat to a failure point. The greater the thermal diffusivity, the faster the material will absorb heat. Consequently, the temperature of a fire in a tin shed (high diffusivity) is going to be less than in a concrete enclosure (relatively lower diffusivity). For a well insulated concrete enclosure the temperature will be even higher.

Effect of temperature

Lie (1995) noted that because the temperatures in a fire enclosure are relatively low during the growth stage of a fire their influence on the fire resistance of the structural members is likely to be negligible. However, after flashover the fully developed period starts and the actual risk of failure of structural members or fire separations begins. In this stage, the heat transferred from the fire to structural members may substantially reduce their strength. This risk also exists in the decay period.

Drysdale (1986) also acknowledged that building elements may fail as a result of high thermal stress during the period of fully developed fire following flashover. Failure of a structural element may cause local or more general collapse of the building structure. The term failure is also applied to compartment boundaries, which may or may not be load bearing, yet "fail" by permitting fire spread into adjacent spaces by flame penetration or excessive transmission of heat.

2.4.3

Property damage

Strategos Report (1989) noted that if fire is suppressed before flashover then damage is more likely to be localised to part of the room of origin, but with possibly smoke and soot stains throughout the structure. Any burning after flashover greatly increases the cost of damage. Items of property (whether structure or contents) need not be totally burnt in order to have lost all value. A building and contents may be a "total loss" long before the building is burnt down.

Beck (1989) also acknowledged that fires which develop to the post-flashover stage can cause substantial property damage. Those post-flashover fires spreading beyond the zone of fire origin contribute significantly to the overall property damage, since they can involve an entire large building and, in some cases, spread to adjoining buildings.

2.4.4

Tall buildings

The need in tall buildings to contain fire and prevent structural collapse is paramount, in comparison to the need in low-rise structures. The practical outcome of a post-flashover fire, should it develop in a tall building, depends on the integrity of the fire compartment boundaries, and that of structural element protection systems. A fire safety response, in terms of “controlling fire by construction”, is explained in Section 2.5: Responses to Building Fire Risk.

Scawthorn (1992) noted that when flashover occurs in a tall building the risk levels are greater, in comparison to those of a low-rise structure, both for the occupant exiting and for fire-fighters accessing the effected areas. For this reason, emphasis needs to be placed on the control of early fire spread through design and construction features. In this way the initial fire is isolated and fire-fighters will have sufficient time to control a growing fire before it spreads from the immediate area of origin. Features found in contemporary tall buildings such as fire-rated doors and walls and fire-rated floor-ceiling assemblies are used to prevent this unwanted fire spread.

2.5 Responses to building fire risk

2.5.1

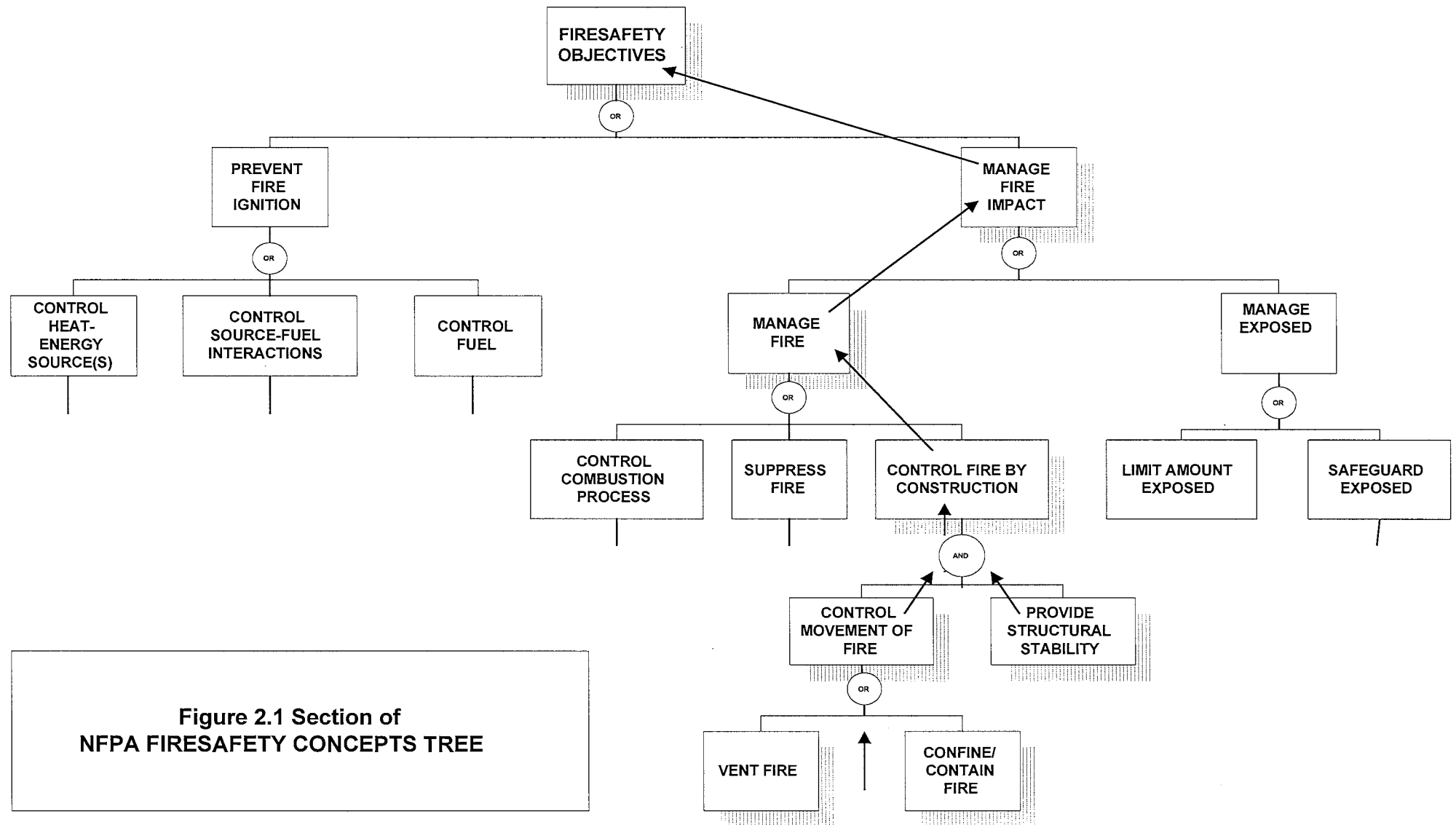
Strategos Report (1989) noted that there is virtually no possibility of eliminating fire hazard completely and to seek to achieve such ends is counter-productive. Rather, it is an issue of finding the best method of managing fire hazard through understanding it and the responses to it. These responses may be in various forms including reliance on fire services, insurance, sprinklers, fire drills, non-flammable building materials and the like.

Reducing fire hazard is, therefore, not costless. According to Strategos Report there is an economic perspective to it, and there will be in most situations an appropriate level of cost for fire hazard reduction which balances the benefits of reducing the hazard.

2.5.2

The recognition that a series of high-rise building fires in the USA in the 1960's were a symptom of the fragmentation of approach in building fire protection lead to the development by the National Fire Protection Association (NFPA) of a logic diagram for fire safety.

This is known as the Firesafety Concepts Tree (coded NFPA 550), and has been described in Roux (1989) as providing a system approach to fire safety, and by being structured in a success tree form it creates a positive view of fire protection in buildings. A section of this tree has been reproduced in Fig.2.1 for use in this Report. The bold arrows indicate the direction of progression through the tree for the example given.



**Figure 2.1 Section of
NFPA FIRESAFETY CONCEPTS TREE**

Basically, the tree presents a logic network for making decisions and design choices to configure the fire safety system in an order that will enable meaningful results. The success of the final design is dependant on the degree of completeness for each level of the fire safety system. Lower levels on the tree do not indicate a lower level of importance. They are instead a means of achieving the preceding (higher) level.

The tree can be used for the design of new buildings as well as for renovation of existing buildings, according to Patterson (1993).

With reference to the Firesafety Concepts Tree, Roux noted the fire safety objectives as being:

- safety to life
- protection of property
- continuity of operation.

Success in meeting these objectives is possible either:

- by preventing fire ignition
(ie to prevent the initiation of destructive and uncontrolled burning)
- or
- by managing the fire impact
(ie to use measures to limit any harm directly or indirectly resulting from fire and / or fire products)

According to Patterson the “Prevent Ignition” branch of the fire safety concepts tree is essentially a fire prevention code. He acknowledges that, basically, it is not possible to prevent the ignition of fire in a building without complete and continuous surveillance of the building operation and all incoming materials. Most of the activities under this branch are under the control of the owner / occupant, and not the building designer. However, an effective programme of fire prevention under this branch eliminates the necessity for any other means, assuming that the fire safety strategy requires no backup system.

Roux has suggested that the “Manage Fire Impact” branch of the tree might be considered to be a building code. He described the two courses of action to manage fire impact as, either.

- manage the fire
(ie use measures for control of the fire and for fire products), or
- manage exposed
(ie coordinate measures directly involving exposed persons, pieces of property, activities, or other valuable considerations).

Managing the fire allows three courses of action, either.

- control the combustion process
(ie control the inherent fire behaviour), or
- suppress the fire
(ie perform actions on a fire process, either automatically or manually, in order to limit the growth of or to extinguish, the fire), or
- control fire by construction
(ie control or limit the growth of the fire and the movement of the flame, heat, smoke,

and gas, by performing actions involving building construction features such as fire barriers, time-rated walls, partitions and ceiling assemblies, and built-in equipment without intentionally acting upon the inherent fire process).

Control of fire by construction is the essence of structural fire design, whose intention is to use structural design, and materials selection and installation, to manage the impact of fire.

Control of fire by construction is the path identified by the arrows in figure 2.1. It requires two courses of action:

- control the movement of the fire
(ie control by providing and activating building construction features and built-in equipment) AND
- provide structural stability
(ie maintain the effectiveness of building construction features and built-in equipment)

Control the movement of fire allows two courses of action, either.

- vent fire
(ie provide building construction features and built-in equipment that can control fire by removal of the fire and / or fire products by venting outside the building through openings, and thus preventing the fire from advancing by eliminating heat build-up in forward areas), or
- confine / contain the fire
(ie provide building construction features and built-in equipment to limit the fire and / or fire products to within the barriers surrounding the area where the fire originated).

Therefore, a response to building fire risk which is based on the “management of the fire” (ie as expressed in the NFPA Firesafety Concepts Tree) can be achieved through structural fire design, whose intention is to control the movement of fire and to provide structural stability.

2.6 Conclusions

2.6.1

By examining the interactions between fire and buildings under normal conditions, this chapter establishes a basis for the report to consider in Chapter 8.0 how the dynamics of fire in buildings are modified by earthquake effects.

The interactions between fire and buildings, and appropriate responses, have been reviewed by considering:

- conditions required for fire in buildings
- the concepts of fire load and fire severity
- growth and spread of fire within and between buildings
- resultant levels of damage
- responses to building fire risk in terms of fire safety measures, defined on a logical basis.

2.6.2

The main conclusions are:

1. For combustion to occur specific conditions need to be present in terms of the ignition heat / fuel / oxygen combination. Under normal conditions, and for fire initiation, the first two factors are the critical ones since they define the extent that a fire hazard is present and could lead to fire losses. The fire load of a building represents the latent energy available for fire but is not a complete indication of the severity of a potential fire.
2. Fire burn rate and the duration of burning depend on a more comprehensive set of conditions determined by the nature of the fuel and its arrangement, and also by building design. These also define the maximum fire temperature reached and the time for which the maximum temperature persists (ie. fire severity), and these are the fire conditions determining the fire's potential to destroy or damage the building, the contents, and adjacent property.
3. The temperature course of a fire in a room may be divided into the three periods: fire growth period, fully developed burning period and fire decay period. Fire temperature and hence damage is increasing during the growth period and maximises during the stage of fully developed burning. The window of opportunity for effective fire loss reduction therefore progressively diminishes during the fire growth period and is lost totally at the transition to fully developed burning.
4. Horizontal and vertical fire spread beyond the room of fire origin may be controlled by fire-rated barriers such as walls and ceilings, but the effectiveness of these can be compromised by openings which may include doors, apertures and services penetrations that have lower, or zero fire-rating. The restoration of barriers to their full fire resistance ratings through attention to the fire-rating of those elements which compromise barriers' fire and smoke control performance represents an opportunity for effective fire loss control.
5. Fire spread via the outside of the building is an extreme condition which may occur even if vertical fire spread within the building is effectively controlled by interfloor fire separations. The extent that fire may spread in that way can generally be limited by building design and material specification, which may include aspects of building geometry, window dimensions and fenestration, and the extent of use of horizontal apron projections, and of non-combustible exterior wall claddings.
6. Three causes of fire spread between buildings are:
 - a). by the transfer of heat by radiation, which is the severest condition causing the ignition of
 - combustible exterior features of an adjacent building
 - combustible contents through windows of an adjacent building
 - b). by the transfer of heat by convection, which is of relatively limited range ie. for separations of 1 - 2 metres, and is by hot gases and flames emerging from the burning building and impinging on
 - combustible exterior features of an adjacent building
 - combustible waste or shrubs between buildings which provide an unbroken

fuel chain for the transference of flame to an adjacent building, and possibly assisted by wind or by the topography of the surrounding area eg. steep hill suburbs.

c). by wind-borne fire brands, causing spot ignitions of a building(s) downwind of the main fire.

7. Fire damage is caused by:

a). the fire heat generated and its effects on materials, particularly on the buildings' structural components whose structural integrity after fire extinguishment will depend on the thermal properties of those materials and on the effectiveness of insulative systems during the fire

b). products of combustion, which are most evident in the smoke produced and whose type, corrosivity and toxicity are a direct result of the materials under combustion.

8. Risk of failure of structural members or fire separations begins after the fire has reached its fully developed phase, and exists during its decay phase. Items of property whether structural or contents, need not be totally burnt in order to have lost all value.

9. There is a special need in tall buildings to contain fire by fire compartment boundaries and to prevent structural collapse, particularly for occupants exiting and for fire-fighters accessing effected areas to control a growing fire and prevent fire spread.

10. Responses to building fire risk are either:

a). to suppress the fire, or

b). to control the fire by containing it within fire compartment boundaries and by providing structural stability.

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CHAPTER 3.0

THE ROLE OF PASSIVE FIRE PROTECTION SYSTEMS IN BUILDING FIRE SAFETY

3.1 Background

3.1.1

This chapter builds on issues raised in Chapter 2.0 concerning the interaction between fire and the built urban environment by examining how the control of fire in buildings is achieved by passive construction features. Urban macro-scale passive fire protection is also discussed.

3.2 Passive systems in building fire safety

3.2.1

Passive fire safety systems are defined in Beck (1989) as those elements in a building which may contribute to increased fire safety but are characterised by the following:

- do not require activation by fire effects or products to carry out their intended purpose
- are self-contained or independent in action
- are not intentionally acting upon the inherent fire process.

Examples given are fire barriers, time-rated walls, partitions and ceiling assemblies, and built-in equipment.

Patterson (1993) included smoke control barriers, and pressurisation, venting, curtain and reservoir systems as passive fire safety systems.

The major role of passive systems in fire safety is noted by Beck to be that of barriers to the spread of fire or the effects of fire.

Stollard and Abrahams (1990) acknowledged that it is fire heat which is most dangerous to the building structure, and smoke which is most dangerous to the occupants. Therefore, it is necessary to have containment measures which tackle both these risks, and stop the spread of both smoke and heat.

Fire containment provides the opportunity of achieving the fire safety objectives of property protection and life safety:

- property protection through the limitation of fire spread, and through fire resistance provided to the elements of the building's structure
- life safety through the limitation of smoke spread, and through the provision of places of refuge within the building to which occupants can retreat.

Stollard and Abrahams note that whether or not a fire is detected and the communications system alerts people and equipment to take counter-measures, the design of the building should be such that the fire is contained and limited. Fire

containment should be the “fail safe” tactic which the designer has provided, even if all other measures are ineffectual

Fundamental to all fire safety schemes and as noted by Patterson, is the ability of a building to contain fire for some predictable period of time in order for all of the planned fire safety strategy measures to be activated and carried out.

3.3 Passive systems as barriers to the spread of fire

3.3.1

Passive measures of fire containment concern the nature of the building structure, and of the building subdivision and envelope. They will last the life of the building and will always be available as a defence against fire spread.

According to Stollard and Abrahams, such passive measures can be considered under three headings:

1. Structural protection - the protection against the effects of heat provided to the structural elements of the building (ie columns, load-bearing walls and floors).
2. Compartmentation - the division of the building into different areas, and the resistance to fire and smoke offered by such subdivision (ie internal walls, doors and floors).
3. Envelope protection - the protection offered by the envelope of the building to both the surrounding properties / people from a fire within the building, and the building itself / occupants from a fire in adjoining property (ie external walls and roofs).

Beck has noted that elements providing an enclosing or separating function can form a barrier in several ways. They may:

1. Prevent the spread of cool smoke or combustion products.
2. Prevent or delay the spread of hot smoke or combustion products.
3. Prevent or delay the spread of heat by radiation, or by conduction, or by convection.
4. Prevent or delay the spread of flames (very hot combustion products).

3.3.2

During the course of a fire, barriers may be changed or be affected in their physical properties or appearance. Beck has noted that the role of a particular passive system acting as a barrier to the spread of fire or its effects is dependent on the particular fire scenario eg. ignition / smouldering, established burning or flashover. This relationship is based on time, and involves the following opposing issues:

- the time period over which the passive system is required to act as a barrier
- the time over which the barrier’s effectiveness degrades in the fire.

Botting and Buchanan (1998) noted that containing elements such as fire resisting walls may suffer cracks or other damage during an earthquake, which could compromise their fire performance.

According to Beck, the success of a passive system depends on burnout or extinguishment occurring before its effectiveness as a barrier is lost.

3.4 Characteristics of passive barrier systems that relate to performance

3.4.1

The characteristics of passive barrier systems that relate to performance have been reported in Beck (1989) to include the following:

- material combustibility
 - surface combustibility of barriers clearly influences their performance over time, but at the time of reporting there were no calculation procedures which evaluated rates of combustion as a factor in barrier degradation. It is nominally taken into account through building code criteria requiring the use of non-combustible materials as barrier elements.
- integrity / continuity
 - this is the dominant performance characteristic for many barriers. Two ways of interpreting this were suggested; either in terms of the effect of the presence of an opening in a barrier (eg. door, which must be treated so that it has at least the same level of performance as the barrier itself, if it is to restore the barrier to a full level of effectiveness); or in terms of the barrier's performance under fully developed fire conditions, when small gaps and holes may open up and permit the passage of smoke and flames to the adjoining enclosure.
- construction quality / maintenance considerations
 - these have a significant impact on barrier performance as they can influence the continuity and integrity of barriers, and hence their reliability.
- insulation / opaqueness to radiation
 - the importance of these factors in preventing fire spread had not been evaluated; barriers to the spread of heat are designed to prevent the ignition of combustible materials on the other side of the barrier. Beck suggested that this was a very uncommon form of fire spread, largely because the times and temperatures required are such that other fire related events (such as the initiation of sprinklers or the loss of integrity of the element) are likely to occur first.
- resistance to collapse
 - post-flashover resistance to fire has been the traditional role assigned to barriers in building codes, and is a characteristic well understood and quantified. Performance of systems has been traditionally evaluated by standard testing eg. AS 1530.4 and rational calculation procedures established to predict performance of steel, concrete and timber systems.

3.5 Opening treatments

3.5.1

Openings in barriers, such as open doors or windows, or small gaps or holes in a wall or floor, represent the “weak links” in passive systems and must be considered as reductions in the barrier’s capability for resisting smoke and fire spread.

Opening treatments are defined in Beck (1989) as closures which may or may not be specifically designed to prevent the spread of fire or its effects between enclosures linked by the opening eg. closed doors or windows, pipe penetration sealants, duct dampers, fire stopping etc. Although opening protectors control the spread of products of combustion prior to flashover (and this is especially important when the safety of people is being considered), building codes recognise the need for these elements in the post-flashover fire scenario through fire resistance requirements for opening protectors, and for these to be matched to the barrier requirements.

The penetration of separating elements by ducts, conduits, pipes and cables, and numerous other items, although essential in many buildings may also link more than one building space, and create the same weaknesses in barrier effectiveness as doors and windows. Beck noted that their presence automatically increases the probability of the separating element which they penetrate not functioning effectively, although because of their size they may tend to have more influence on the spread of smoke and products of combustion rather than fire spread.

3.5.2

Requirements of opening treatment systems according to O’Hara (1994) are that they:

- must be held securely in place
- can handle the expected environmental conditions
- effectively seal the opening to restrict the passage of smoke, flames, and hot gases, and to restrict the transfer of heat to the unexposed side.

O’Hara noted that “fire-stopping” is a rather ambiguous term commonly used to describe a type of protection in combustible construction with a material (such as mineral wool, wood blocks or gypsum boards) that is securely fastened in place. This has been re-defined by the NFPA, using the term “through-penetration protection systems” (TPPS) and described as being:

“Specific building materials or assemblies of materials that form a system designed to prevent the spread of fire for a prescribed time period through openings made in fire-rated floors and walls to accommodate the passage of combustible and non-combustible items such as pipes, tubes, conduits, vents, wires, and electrical cables”.

The adequacy of the fire performance of a TPPS can be assessed by test methods such as those defined by ASTM E 814: 1981, Standard Method of Fire Tests of Through Penetration Fire Stops. O’Hara noted that the performance of the TPPS when exposed to a standard test fire depends on the specific assembly of the materials tested. However, he contended that TPPS must be tested for more than their performance during a fire. They must also be able to withstand the wear and tear of building operations, including the movement of the penetrant and the building itself, and such environmental conditions as temperature, humidity and corrosion.

The test methods in ASTM E 119 (NFPA 251), Fire Tests of Building Construction and Materials are meant to evaluate the length of time wall, ceiling, and floor assemblies will retain their structural integrity when exposed to a standard test fire. According to O'Hara the methods can be used to test the fire endurance of TPPS only when the latter have been specifically provided for in the assembly tested.

3.5.3

Seismic gaps are spaces between adjoining buildings, or spaces within buildings, which are expected to open and close during an earthquake. If the fire design requires these gaps to be filled with fire resistant material to prevent fire or smoke, that filling material must be able to accommodate the expected movement. For more information see James (1997).

A fire test method for construction joints is UL 2079, Standard for Fire Tests of Joint Systems, covers floor-to-floor, wall-to-wall, floor-to-wall, and wall-to-floor-joint systems, and according to O'Hara, also identifies dynamic and static joints, movement capability, and manufactured and field splices.

3.6 Protection of the building structural frame

3.6.1

Beck (1989) noted that the structural frame of a building may form part of the system of separating elements, it may be protected by that system, or it may be protected (if necessary) by an independent protection system.

According to Botting and Buchanan (1998) structural fire protection systems are not tested for earthquake movement but they have to be tough enough to remain in place when subjected to large deformations in fire resistance tests, which means that they will have some ability to accommodate movement from earthquake.

The structure of a building is generally only seriously affected in extreme post-flashover fire conditions. At that time, and according to Beck, the role of the structural frame of a building in fire safety depends on the type of building under consideration and on the fire safety philosophy being employed.

He noted that in achieving the desired level of fire safety:

- there may be a major role for the structure, and it may be unacceptable for the building to collapse in even the largest foreseeable fire eg.
 - where evacuation is a lengthy process
 - or where great value is placed on the building itself or on the contents
- or there may be virtually no role for the structure, and it may be perfectly satisfactory to have the structure eventually collapse in the event of a fire eg.
 - where it can be readily evacuated
 - and where little value is placed on the building itself
 - and provided no harm is brought to adjacent buildings.

Traditionally, building code requirements have addressed structure protection from the point of view of protection of the building and its contents. Beck acknowledges that today's building codes focus on the safety of the building's occupants.

3.7 Smoke control

3.7.1

Patterson (1993) included smoke control by barriers, and by pressurisation, venting, curtain and reservoir systems, as passive fire safety systems, but noted that the problem of smoke control is a separate problem to that of fire control by passive means.

According to Patterson, the main requirements of these systems are for:

1. Control by smoke barriers

- to compartmentise the building into "smoke cells" and to limit the spread of smoke, in the same way that fire is limited (they may fall at the same intervals and positions as fire walls, but barriers which are adequate for fire control may not be adequate as smoke barriers).
- to be continuous
- to have doors which are smoke control duty, be self-closing or automatic-closing, and where doors are required to remain open because of operational necessity be fitted with hold-open devices controlled by an automatic fire alarm system
- to have smoke dampers provided at each air-transfer opening or duct penetration (obviously excepted from this requirement are ducts which are part of an engineered smoke control system and other air handling components specifically designed to activate and relieve emergency fire conditions).

2. Control by pressurisation

- to maintain a supply of fresh air in the protected area (normally a small well-defined space) at a pressure slightly above that of the adjoining spaces such that when doors are opened into the protected area the air from the area flows out, rather than smoke flowing in. When they are closed, the positive pressure maintains a continuous outflow of fresh air through whatever leakage is present in the smoke barrier components, rather than smoke leaking in).
- to provide pressurisation in a single stage (in which case they are designed to act only in the event of fire), or in two stages (where they act continuously at some pressure differential, and then increase that differential upon signal from the fire alarm system). Two-stage systems are preferable in most applications because they are already on and give some measure of fire protection even before official detection by the alarm system
- to provide (in ideal applications) pressurisation in the entire means of egress.

3. Control by smoke venting

- to prevent the development of smoke build-up within a building (particularly in large spaces)
- to ensure adequate venting system capacity such that hot smoky gases are expelled at the same rate as combustion products are being produced by the fire (products are expelled via a built-in roof vent(s) or through exterior walls, or through corridor walls into adjacent spaces designated for the purpose of smoke accumulation during a fire, and hence to the outside)

- to provide a layer of smoke-free cold air at floor level for the evacuation of occupants and access to the fire by fire-fighters (by Buchanan (1995) and with reference to s/s 9.7 a design minimum fresh air layer height is 1.5 metres).

Notes: Issues critical to the design of venting systems include those given by Patterson as the effects of natural ventilation, air flow around the building itself, the placement of fresh air intakes, and the capacity of the mechanical air handlers in use. Sizing of vents will relate to the containment, and release of smoke build-up within a smoke reservoir (see 5. below).

4. Control by smoke curtains

- to limit and control the horizontal growth of smoke by means of smoke curtains or “curtain boards”, either permanently in place or designed to be dropped under the control of the building fire detection system
- to allow as necessary for varying degrees of protection and control in areas of a building by providing curtain boards of reducing depths to induce smoke movement in the direction of less critical occupancy.

5. Control by smoke reservoirs

- to either contain, or alternatively to contain and progressively release smoke build-up in association with a venting system.

Notes: Smoke containment may be possible within high vaulted roofs and atriums, or reservoirs incorporated into roof design. The maximum size of smoke reservoirs is a critical factor to the avoidance of the cooling and settling of smoke towards floor level.

3.8 Urban macro-scale passive fire protection

3.8.1

Consideration of passive fire protection for building fire safety is broadened by Chung (1996) to include city-wide, or urban, macro-scale fire protection achieving fire separations between fire loads ie buildings and other structures by means of:

- city blocks consisting of buildings of non-combustible construction
- wide roadways
- parks, sports grounds etc.

Kenna (1975) noted that towns which have closely spaced buildings, narrow streets and few green belts represent high fire risks.

3.8.2

The following issues have been identified as possibly offering scope for further research:

1. Construction requirements for fire resistive buildings, especially for the protection of openings such as windows and doorways.
2. Practical requirements for and means of implementation of fire resistive egress corridors for cities.

3.9 Conclusions

3.9.1

This chapter examines the issue of how the control of fire in buildings is achieved by passive construction features. Urban macro-scale passive fire protection is also discussed.

3.9.2

The main conclusions are:

1. The major role of passive systems in building fire safety is to provide barriers to the spread of smoke and heat. This is the “fail safe” protection which is available even if other fire counter-measures are ineffectual.
2. Building fire protection by passive measures can provide structural protection, compartmentation and envelope protection.
3. Barriers may be changed or be affected in their physical properties or appearance during the course of a fire, but the extent of change is dependent on the particular fire scenario eg. ignition / smoldering, established burning, or flashover, and involves the opposing issues of -

a). the time period over which the passive system is required to act as a barrier

b). the time over which the barrier’s effectiveness degrades in the fire.

The success of a passive system depends on burnout or extinguishment of the fire occurring before its effectiveness as a barrier is lost. Barriers such as walls may, however, suffer cracks or other damage during an earthquake which could compromise their fire performance.

4. Performance-related characteristics of passive barrier systems include the extent that barrier elements -
 - a). are non-combustible
 - b). have consistent and adequate fire-resistance rating over their entire exposed area
 - c). are reliable through adequate construction and maintenance
 - d). are resistant to collapse under post-flashover conditions.
5. Openings in barriers eg. open doors and windows, small gaps or holes in a wall or floor, or penetrations by ducts, conduits, pipes and cables etc. reduce barriers’ capability for resisting smoke and fire spread. Opening protectors are recognised by building codes as requiring to be matched to the barrier requirement to -
 - a). effectively seal the opening to restrict the passage of smoke, flames and hot gases, and to restrict the transfer of heat to the unexposed side

- b). be held securely in place and withstand wear and tear of building operations, including the movement of the penetrant and the building itself
- c). be able to handle the expected environmental conditions of temperature, humidity and corrosion.

Test methods are available to confirm the adequacy of the fire performance of assemblies and systems when exposed to a standard fire, such as those defined in ASTM E 119 (NFPA 251) for wall, ceiling and floor assemblies, ASTM E 814: 1981 for through-penetration protection systems, and UL 2079 for joint systems.

6. The role of the structural frame of a building in fire safety depends on the type of building under consideration and on the desired level of fire safety -
 - a). structure may have a major role during and after the fire, and it may be unacceptable for the building to collapse in even the largest foreseeable fire eg. because evacuation is a lengthy process, or the building or its contents have great value, or safety of neighbouring buildings would be endangered.
 - b). structure may have virtually no role after a fire eg. because it can be readily evacuated, or no value is placed on the building, or no harm is brought to adjacent buildings.

The structural frame of a building may be part of the system of fire separating elements, may be protected by that system, or it may be protected by an independent protection system.

Structural fire protection systems are not tested for earthquake movement but they have to be tough enough to remain in place during large deformations in fire resistance tests, which means that they will have some ability to accommodate some movement from earthquake.

7. Barriers for fire control by passive means may not be adequate to prevent the spread of cool ie. ambient temperature smoke or combustion products. Hence smoke control by barriers is a separate problem from that of fire control, and smoke barriers are required to compartmentise the building into "smoke cells" to limit the spread of smoke. They may be at the same intervals and positions as fire walls. Doors in smoke barriers must have smoke control duty and be self-closing or automatic-closing.
8. Other techniques for smoke control are -
 - a). control by pressurisation, to stop the inflow of smoke into a protected area eg. a compartment or an entire means of egress, either through open doors or through gaps in smoke barrier components. Two-stage systems are preferable in most applications because they are already on and give some measure of fire protection even before official detection by the alarm system
 - b). control by smoke venting, to prevent smoke build-up within a building and to maintain tenable conditions for occupant evacuation and access to the fire by fire-fighters

- c). control by smoke curtains, to limit and control the horizontal growth of smoke, or to induce smoke movement in the direction of less critical occupancy
 - d). smoke reservoirs, to contain smoke build-up or alternatively contain and progressively release it in association with a venting system.
9. The risk of major urban post-earthquake fire losses can be reduced through the elimination of high concentrations of buildings with combustible claddings and their replacement with fire-resistant buildings, and by providing wide roadways, parks and other open spaces.

CHAPTER 4.0

THE ROLE OF ACTIVE FIRE PROTECTION SYSTEMS IN BUILDING FIRE SAFETY

4.1 Background

4.1.1

This chapter gives further consideration to the issues raised in Chapter 2.0 concerning the interaction between fire and the built urban environment, by examining how the control of fire in buildings is enhanced by active fire protection systems.

4.2 Active systems in building fire safety

4.2.1

Active fire protection systems are those which require activation by fire effects or products to carry out their intended purpose. By their nature they are dynamic ie. they are characterised by time dependent performance.

According to Beck (1989) the dynamic nature of active fire protection systems carries with it the need for performance testing and maintenance throughout their service life to ensure that the performance achieved at commissioning is subsequently available in their “through life” state.

4.2.2

Elements and systems intended to provide active fire protection cover a significant range, which includes:

- detection and alarm equipment
- suppression systems
- exit and emergency lighting
- automatic doors, and fire dampers
- smoke management systems eg. mechanical smoke exhaust systems
- supporting services eg. power and water supplies.

4.2.3

The primary goals in fire protection are noted in Schifiliti (1995) as:

1. Life safety.
2. Property protection.
3. Business protection.
4. Environmental concerns.

Depending upon the specific protection objective(s) at hand, the weight of an individual goal may vary. Schifiliti has identified design criterion for the provision of active fire protection systems, and as required for the achievement of the individual goals:

1. Life safety
 - early warning of a fire condition is necessary. The fire detection and alarm system must provide a warning early enough to allow complete evacuation of the danger zone before conditions become untenable. The fire alarm system may be used to activate other fire protection systems eg. smoke control systems, to help maintain a safe environment during a fire and facilitate Fire Service operations.
2. Property protection
 - the objective is to limit damage to the building and contents, hence the goal is principally economic, and the fire protection system must detect a fire soon enough to allow manual or automatic extinguishment before fire damage exceeds acceptable levels.
3. Business protection
 - the objective is to limit fire damage to the extent that undesirable effects on the business or mission are prevented.
4. Environmental concerns
 - the protection of the environment is also a fire protection concern as damage could be done by a cause such as the toxicity of products of combustion, or contamination by fire protection run-off water. Should large quantities of contaminants be expected from a large fire, the goal of the system may well be to detect a fire and initiate appropriate response prior to reaching a pre-determined mass loss from burning materials, or quantity of fire suppression agent discharged.

4.3 Fire alarm systems

4.3.1

Bukowski and O'Laughlin (1994) defined a fire alarm system as one that is primarily intended to indicate and warn of abnormal conditions, summon appropriate aid and control occupant facilities to enhance protection of life. The system might also be designed to initiate operation of a fixed extinguishing system such as a deluge sprinkler system or a total gas flooding system, for the protection of a special hazard, or of a specific risk..

The three basic elements of a detection and alarm system, as defined by Schifiliti, are:

1. Detection
 - that part of the system that senses fire
2. Processing
 - involves the processing of signals from the detection portion of the system
3. Signalling
 - the signalling portion is activated by the processing section in order to alert occupants, and to perform other auxiliary signalling operations which include fire department signalling, activation of a smoke control system(s), elevator capture, and door closing.

4.3.2

A fire detector is a device with a pre-set sensitivity level: when the area (or condition) immediately surrounding the detector exceeds those pre-set parameters, a signal is produced.

From the moment of initiation, fire produces a variety of changes in the surrounding environment. Bukowski and O’Laughlin described these changes in the ambient conditions as “fire signatures”, and any of these can be monitored by a detection system.

These include the following:

- energy release signatures eg. infra-red, ultra-violet, and thermal energy
- evolved gas signatures. During a fire many changes occur in the gas content of the atmosphere both in the area of fire origin and in areas far removed from the fire. Gases evolved are typically CO, CO₂, HCl, HCN, HF, H₂S, NH₃ and nitrogen oxides.

Fire detectors sense one of the three parameters:

1. Convected heat (by thermal, or heat detectors, including sprinklers).
2. Smoke particles (by ionisation, photo-electric, and aspirating smoke detection).
3. Radiated energy released by combustion (by infrared and ultra-violet flame detectors).

Much of the hardware associated with the detection and suppression of fires in commercial, manufacturing, storage, and recently constructed residential buildings is located near the ceiling surfaces. Evans (1995) explained the effects of ceiling jet flows produced by a fire: hot gases in the fire plume rise directly above the burning fuel and impinge on the ceiling. The ceiling surface causes the flow to turn and move horizontally under the ceiling to other areas of the building remote from the fire position. The response of smoke detectors, heat detectors, and sprinklers in this hot flow of combustion products from a fire provides the basis for the building fire protection.

4.4 Suppression systems

4.4.1

The term “suppression” has been defined in Beck (1989) as the measures taken to contain fire spread to within the enclosure of fire origin, and to the point where manual extinguishment can be undertaken.

Suppression systems will have a primary effect on fire development, on fire spread, and on the development of otherwise untenable conditions. In doing so, secondary effects benefitting life safety and reducing the extent of property damage, may occur.

Fire sprinkler systems and water spray systems are the most efficient means currently available for suppressing fires by the use of water in most types of occupancies. According to Buchanan (1995) this is because they operate when the fire is small and only over the area affected by the fire. Water streams from fire brigade hoses may be less efficient than a well-directed spray of water, such as from a sprinkler head, and generally result in considerably greater water supply demand and a greater run-off of water. Additionally, the fire is allowed to grow to a larger size before the application of

water to the fire, mainly because of the inevitable delay in Fire Service operational fire-fighting resources getting to the fireground.

Strategos Report (1989) also acknowledges sprinklers to be a proven means of controlling and suppressing fire early in the fire growth curve, and do not cause the amount of water damage which is commonly supposed. The Fire Service may still be required to attend a fire, but it is unlikely to need to deploy the same amount of resources as in the case of a fire in an unsprinklered structure.

Fleming (1995) noted that even in cases where water from sprinklers will not suppress the fire, the cooling ability of water spray can protect structural elements of a building, containing the fire until it can be extinguished by other means.

4.4.2

There is increasing reliance on effective sprinkler performance not only in the New Zealand Building Code but also in other legislation such as the Fire Safety and Evacuation of Buildings Regulations. NZS 4541:1996 recognised this by introducing the threshold for mandatory shift to dual water supplies, based on (with reference to its Clause 601) building floor area (>11,000sq.m.), or height (>25m), or seismicity of the location (Zone factor >0.6).

Buchanan (1995) identified the need to consider water supply reliability so that assumptions of water at a particular point in the fire growth curve will prove valid at the time of the fire, and noted that reliability issues include earthquake damage.

The need for the provision of on-site water storage and pumping capacity sufficient to protect the fire risk is recognised in NZS 4541:1996, which nominates three classes of water supplies, and these provide different levels of reliability and availability in the water supply.

These are:

- Class A - Dual superior supply: two fully independent water supplies such as a town main and a tank and pump system
- Class B - Dual standard supply (Class B1 and Class B2):
 - Class B1: two independent town main water supplies; reticulation is arranged such that at least one supply always remains available should a breakdown occur in any on part of the system
 - Class B2: private site water main in accordance with s/s 61 of the Standard
- Class C - Single supply: one approved primary supply.

The Building Act and the Building Regulations 1992 indirectly create requirements for water supplies for fire-fighting purposes by stating that:

- buildings must be provided with fixed fire protection systems (as defined in Building Code Acceptable Solution Annex to Fire Safety Documents Appendix B)
- availability of a water supply is one of the factors influencing the required level of fire resistance for the structural stability of primary elements, to avoid premature failure under fire conditions (as noted in Building Code Acceptable Solution AS C4/AS1, paragraph 1.3 (g)).

4.4.3

Careful testing, compliance inspection and on-going maintenance are essential to ensure sprinkler system reliability. Beck (1989) suggested that subjectively one could equate the commissioning and management systems to improving the reliability of suppression by 4% - 5% (ie. raising reliability from some 90% in the US to some 95% - 96% in Australia and New Zealand). The practice of connecting such systems to the Fire Service in Australia and New Zealand would also have a bearing on both quality control of installations, and encouragement to maintain them, resulting in this local performance increment.

NZS 4541:1996 made a higher claim to reliability by stating that in New Zealand approved sprinklers have achieved their fire control function in better than 99.5% of the fires in which they have operated.

4.4.4

Strategos Report (1989) noted that where sprinklers are used there are “trade-offs” available in building codes in recognition that where sprinklers control fire, other fire defence mechanisms are less necessary.

Scawthorn (1992) cautioned against the mis-use of trade-offs. The elimination of in-place features such as fire-rated walls and doors, because sprinklers are used instead, increases the risk of fire spread in a building in the event of major sprinkler system failures (such could result from earthquake damage), and then neither sprinklers are functional nor passive features are present.

4.4.5

The NFPA Firesafety concepts tree helps to focus the fire protection community on various routes to the “Firesafety objective”.

Fleming (1989) noted that one of these routes is achieved by a properly designed and functioning fire sprinkler system. A section of this tree has been reproduced in Fig. 4.1 for use in this Report. The bold arrows show the direction of progression through the decision tree. Once the automatic suppression system has detected the fire and applied sufficient suppressant so as to automatically suppress the fire, progress in the decision tree through “or gates” directly to “fire management”, to “management of fire impact”, and finally, to the “firesafety objective”, is achieved.

Patterson (1993) noted the other strategy under “suppress fire” which engages the concept “manually suppress the fire”. It can be seen that it requires five enabling events (omission of any one of these five events will disable the entire strategy). These are:

- “detect the fire”, and
- “communicate signal”, and
- “decide action”, and
- “respond to site”, and
- “apply sufficient suppressant”.

If responsible personnel are ever present at the site, then a manual suppression system can be extremely effective because personnel and equipment are already in the vicinity of any potential fire before it occurs. The local fire brigade is usually a backup to this strategy.

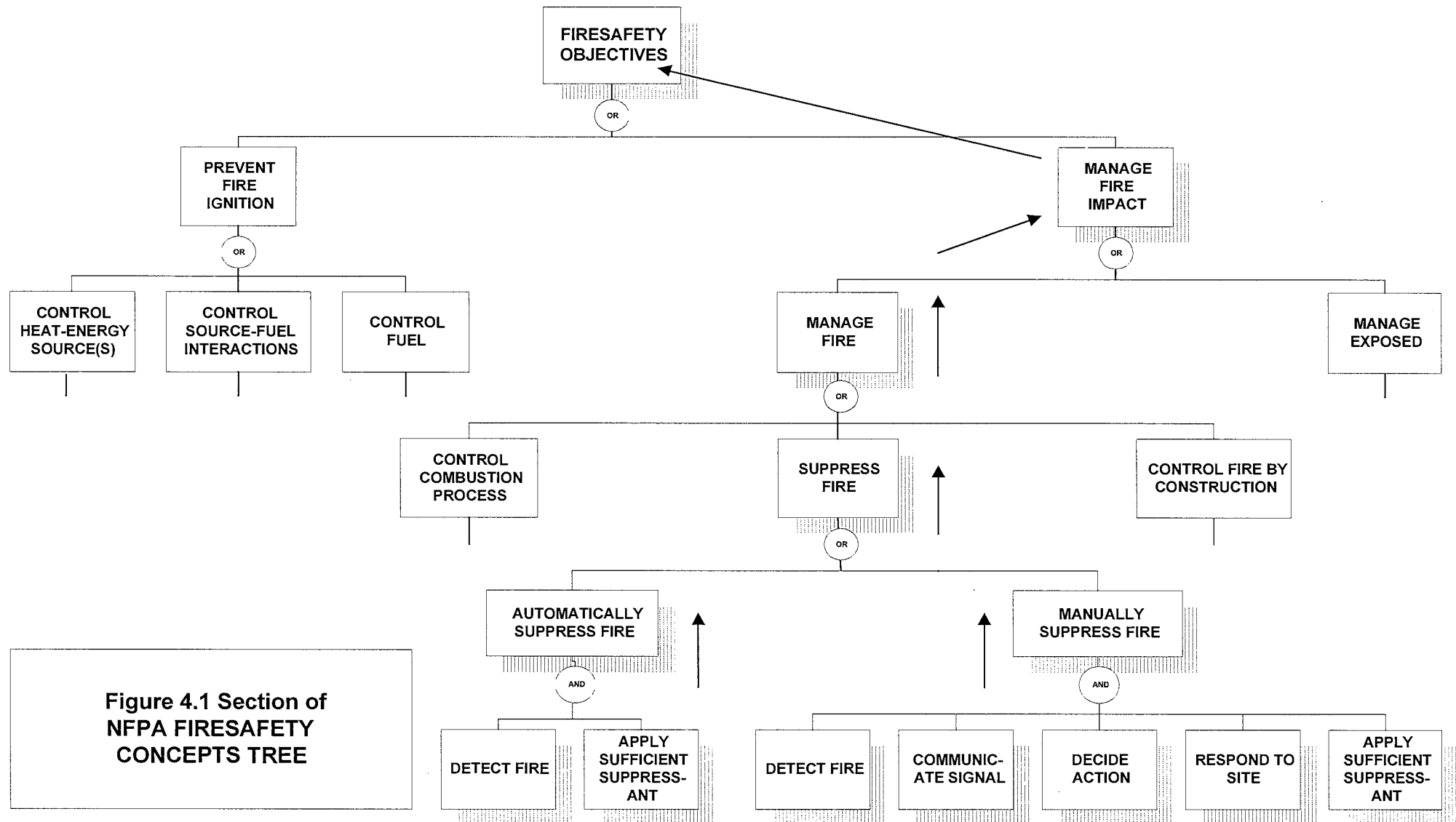


Figure 4.1 Section of
NFPA FIRESAFETY
CONCEPTS TREE

4.5 Conclusions

4.5.1

This chapter examines the issue of how the control of fire in buildings is enhanced by active fire protection systems.

4.5.2

The main conclusions are:

1. Active fire protection systems require activation by fire effects or products to carry out their intended purpose. They are characterised by time dependent performance and need performance testing and maintenance throughout their service life.
2. The design criterion used for the provision of active fire protection systems will depend upon the specific protection objectives -
 - a). for life safety, an early warning of fire conditions is necessary to allow complete evacuation before conditions become untenable
 - b). for property protection, detection of fire is necessary soon enough to allow manual or automatic extinguishment before fire damage exceeds acceptable levels
 - c). for business protection, with detection of fire as for b). and before undesirable effects on the business or mission can occur
 - d). for environment protection, to detect a fire and initiate appropriate response prior to reaching a pre-determined mass loss from burning materials producing toxic products, or a quantity of fire water discharged which may produce contaminated run-off water.
3. Fire alarm systems are primarily intended to -
 - a). indicate and warn of abnormal conditions
 - b). summon appropriate aid
 - c). control occupant facilities to enhance protection of life, and
 - d). may also initiate operation of a fixed extinguishing system for the protection of a special hazard or a specific risk.

The three basic elements of a detection and fire alarm system are detection, processing and signalling

4. "Suppression" are the measures taken to contain fire spread to within the enclosures of fire origin, and to the point where manual extinguishment can be undertaken. Fire sprinkler systems and water spray systems are the most efficient means currently available for suppressing fires by the use of water in most types of occupancies because they operate when the fire is small and only over the area affected by fire. The

fire brigade may still be required to attend but it is unlikely to need to deploy the same amount of resources as in the case of fire in unsprinklered buildings.

5. Even in cases where sprinklers will not suppress the fire the cooling ability of water spray can protect structural elements of a building containing the fire until manually extinguished.
6. Where there is a dependence on the fire brigade for first attack and suppression the fire most likely will grow to a larger size while operational fire-fighting resources are getting to the fireground and setting up. Water streams from fire brigade hoses may be less efficient than a well-directed spray of water such as from a sprinkler head and may generally result in a considerably greater water supply demand and a greater run-off of water.
7. The increasing reliance on effective sprinkler performance and its dependence on water supply reliability is recognised by NZS 4541: 1996. This Standard indicates the threshold for the mandatory provision of dual water supplies for new sprinkler systems as for building floor areas > 11,000sq.m, or building height > 25m, or seismicity of location by Zone factor > 0.6 (where a dual superior supply is required with the primary supply not being reliant on a town main supply).
8. Building codes allow trade-offs where sprinklers are used, in recognition that where sprinklers control fire other defence mechanisms are less necessary. However, the elimination of in-place features such as fire-rated walls and doors because sprinklers are used instead, increases the risk of fire spread in the event of major sprinkler system failure. Trade-offs must therefore be used with caution.
9. One of the ways of managing fire impact is by suppressing fire either through automatic or manual means, and achieved in particular by:
 - a). detection of the fire by an automatic suppression system, and application of sufficient suppressant automatically, or
 - b). detection of fire by a fire alarm system requiring five enabling events of -
 - detection, and
 - communication of a signal, and
 - a decision on the action to be taken, and
 - a response to the site by a fire-fighting force, and
 - the application of sufficient suppressant by a fire-fighting force by manual means.

CHAPTER 5.0

REVIEW OF HISTORICAL DATA

5.1 Background

5.1.1

This chapter explains the rationale of an analysis of historical earthquake data, and how the results have been used in subsequent chapters of this report to establish a detailed appreciation of the impact of post-earthquake fire on the fire protection response of the urban built environment.

5.2 Earthquakes throughout history

5.2.1

Appendix 1 presents details in a tabular form of major earthquakes over the last 400 years. Although not attempting completeness the list includes many events which in their time caused enormous damage and loss of life. Many resulted in post-earthquake fire damage which greatly exceeded the damage caused by earthquake shaking.

5.2.2

Table 5.1 is a date / location summary of those earthquakes referred to above for which more detailed information is provided in Appendix 1.

5.3 Earthquake events selected for detailed review

5.3.1

The project draws on the results of an analysis of the post-earthquake fire impacts on the built urban environment of fourteen major earthquake events, to discuss:

- nature of ignition sources
- mechanisms of fire spread (including urban conflagration)
- condition of fire safety systems
- effects of major earthquake shaking on public water supply systems and the influence on fire-fighting tactics.

Additionally, the Edgecumbe, New Zealand 1987 earthquake was reviewed, to determine the extent of damage to sprinkler systems and water supplies, although no fire incidents were reported at the time.

5.3.2

From these analyses, a detailed appreciation of the impact of post-earthquake fire on the built urban environment has been established. This includes:

- the likely response of built-in fire protection systems, both active and passive, in the aftermath of a major earthquake
- the expected effectiveness of manual fire-fighting measures
- the factors in urban macro-scale passive fire protection which improve the fire risk, and reduce losses and the potential for urban conflagration.

Table 5.1: List of Major Earthquakes over the last Four Hundred Years

Date	Location
1556, January 24	Shaanxi (Shensi) Province, China
1755, November 1	Lisbon, Portugal
1855, -	Wairarapa, NZ
1906, April 18, 5:12am	San Francisco, California
1908, December 28	Messina, Sicily
1915, January 13	Avezzano, Italy
1920, December 16	Gansu (Kansu) Province, China
1923, September 1, 1:58am	Tokyo / Yokohama, Japan
1931, February 2	Hawkes Bay, NZ (Napier Earthquake)
1933, March 10, 5:54pm	Long Beach, California
1935, May 31	Quetta, India
1939, January 24	Chile
1939, December 27	Erzingan, Northern Turkey
1950, August 15	Assam, India
1952, July 21	Kern County, Central California
1957,	Daly City, San Francisco, Northern California
1960, February 29	Agadir, Morocco
1962, September 1	Buyin-Zahra, Iran
1963, July 26	Skopje, Yugoslavia
1964, March 27	Anchorage, Alaska
1964, June 16, 1:01pm	Niigata, Japan
1967, July 29	Venezuela
1970, May 31	Peru
1971, February 9	San Fernando, Los Angeles, Southern California
1972, December 23	Managau, Nicaragua
1976, February 4	Guatemala
1976, July 28	Tangshan, China
1976, August 17	Mindanao, Philippines
1977, March 4	Bucharest
1978, September 16	Tabas, Eastern Iran
1980, November 23	Naples, Southern Italy
1982, December 13	Yemen
1983, May 2, 4:42pm	Coalinga, San Joaquin Valley, California
1984, April 24, 1:15pm	Morgan Hill, Northern California
1985, September 19-20, 7:18am	Mexico City and adjacent areas.
1987, March 2, 1:42pm	Edgecumbe, NZ
1987, October 1, 7:42am	Whittier Narrows, Los Angeles, Southern California
1989, October 17, 5:04pm	Loma Prieta, Northern California
1993, July 12, 10:17pm	Hokkaido Nansei-oki earthquake, Northern Japan
1994, January 17, 4:31am	Northridge, San Fernando Valley, Southern California
1995, January 17, 5:46am	Kobe City, Hanshin District, Japan (also Osaka and Kyoto Cities).

5.3.3

The earthquakes which were reviewed in detail were selected because they had at least some, and in a number of cases had all, of the following characteristics:

- caused serious fires, or even uncontrolled fires, in significant urban population centres
- caused huge damage and financial losses, and significant or even enormous loss of life or human suffering
- had the potential to provide useful information about post-earthquake fire ignition sources, or about fire spread, or how inbuilt active and passive fire protection systems might be affected by the shaking of major earthquakes
- caused some amount of impairment to fire department response, or heavily taxed or even overwhelmed their resources
- may provide information to assist in establishing the likelihood of post-earthquake fire and the level of Engineering Lifelines damage (particularly water supplies and road access), in New Zealand's earthquake prone major population centres.

5.3.4

Table 5.2 lists the earthquakes which were selected for detailed review. For each earthquake the information was extracted from the available data sources using the topic headings listed in Table 5.3. Appendix 2 contains the reviews of selected earthquakes.

Table 5.2: Earthquake Events Selected for Detailed Review

Date	Location
1906, April 18	San Francisco, Northern California
1923, Sept. 1	The Great Kanto (Tokyo / Yokohama), Japan
1931, February 2	Hawkes Bay, NZ
1933, March 10	Long Beach, California
1964, June 16	Niigata, Japan
1971, February 9	San Fernando Valley, Los Angeles, California
1972, Dec. 22	Managau, Nicaragua
1984, April 24	Morgan Hill, Northern California
1985, Sept. 19-20	Mexico City,
1987, March 2	Edgecumbe, New Zealand
1987, Oct. 1	Whittier Narrows, Los Angeles, Southern California
1989, Oct. 17	Loma Prieta, Northern California
1993, July 12	Hokkaido Nansei-oki, Japan
1994, January 17	Northridge, San Fernando Valley, Southern California
1995, January 17	The Hyogo-ken Nanbu Earthquake (The Great Hanshin, or Kobe), Japan

Table 5.3: Template of Topic Headings for Detailed Reviews of Earthquakes

1. The Earthquake	12. Infra-structure damage
2. When	13. Damage to structures
3. Magnitude	14. Fire following the Earthquake
4. Intensity	15. Fire causes
5. Location of epicentre	16. Fire spread mechanisms
6. Areas effected	17. Damage to fire safety systems
7. Earthquake expectancy	18. Effect of earthquake on water supplies
8. Demographic detail	19. Response of the fire department
9. Geotechnical perspective	20. Lessons to be learned
10. Human Toll	
11. Economic loss	

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CHAPTER 6.0

SEQUENCE OF EVENTS AND RESPONSE TO FIRE IN THE AFTERMATH OF A MAJOR EARTHQUAKE

6.1 Background

6.1.1

A key question is:

“How is the fire protection provided in the urban environment changed in the aftermath of a major earthquake?”

This issue will be considered by addressing the following questions:

1. What are the main elements of fire protection in the normal urban environment?
2. What are the general effects of a major earthquake on an urban environment?
3. What are the likely differences between response to post-earthquake fires and response to fires at any other time?

6.2 Main elements of fire protection in the normal urban environment

6.2.1

Chung (1995) described fire protection of the urban environment as being met by a combination of in-place systems and the actions of people.

The in-place systems include:

1. Building construction.
2. Building fire protection systems.
3. Land use.
4. Public and private water supplies.
5. Communications and utility systems.

Actions of people include:

1. Public fire departments.
2. Private fire departments, and employees and individuals trained in first stage fire-fighting.

6.2.2

Under normal circumstances fire events will be responded to by a combination of in-place systems and the actions of highly trained and well-resourced public fire brigades, and provided that an adequate water supply is available fire brigades are generally capable of containing major fires to limit spread.

6.3 The general effects of a major earthquake on an urban environment

6.3.1

An earthquake has the potential to initiate a chain of events. According to Scawthorn (1985) these events may:

- cause fatalities and injuries among people
- damage structures
- damage urban lifelines (eg. municipal water transmission and distribution pipelines, electricity and gas supplies, communications and transportation systems).

6.3.2

Urban lifeline systems are generally considered to be an integral part of a community's infrastructure network. They provide the means and conveyance for daily as well as critical services and products. Chung (1995) noted that when these systems are damaged or made inoperable during a disaster (and these systems have been shown to be particularly vulnerable to seismic effects), the livelihood and recovery of a region and community are directly affected.

Lifelines are likely to be more vulnerable than buildings or other single-site facilities to earthquake shaking and ground displacement. This is because:

- they cover large areas and are susceptible to a wide range of earthquake hazards
- many are buried underground (and it may be difficult to immediately detect damage)
- many are co-located and during an earthquake this can result in serious impacts (one lifeline may fail and cause indirect damage to another eg. gasmain explosion rupturing a watermain).

6.4 Likely differences between response to post-earthquake fires and response to fires at any other time

6.4.1

According to Chung (1992) the process of ordinary fires in the urban environment will generally consist of:

- ignition
- growth
- detection
- report
- response
- suppression activities
- extinguishment (by suppression activities, or due to exhaustion of the fuel).

6.4.2

Although the process of post-earthquake fires will be similar, according to Chung (1995) the fire protection response interactions which occur in the normal urban environment between in-place systems and the actions of people, are likely to be disrupted during and following a major earthquake.

This will be due to any of the following factors:

- likelihood of multiple simultaneous ignitions
- detection delays
- reporting delays
- response of fire brigades
- water supplies reduced or exhausted.

Multiple simultaneous ignitions

These arise from the widespread effects of earthquake. Scawthorn (1986) noted they are the essence of the post-earthquake fire problem, in that fires that would be easily extinguished under normal conditions could have the opportunity to grow and spread over large areas because they are not responded to due to insufficient fire service resources for the number of fires ignited at the same time by the earthquake.

The fire service is the first line of response for a wide range of emergency situations, in addition to fire. Frequently following a major earthquake a large number and wide variety of emergency conditions will exist, and which will include the following.

Detection delays

The earliest detection of incipient outbreaks is of utmost importance. According to Kenna (1975) this is to ensure that minimum manpower and equipment is needed to extinguish the fire. Scawthorn & Khater (1994) noted that the means of discovery of a fire in the post-earthquake environment is often no different from that at other times, although they acknowledge that due to damaged detectors, or distracted observers, ignitions may be undetected for a long period of time, resulting in large fires which are more difficult to extinguish.

Reporting delays

Reporting delays can be caused by the failure of communications systems through direct external damage and overload from high usage levels. EERI (1985) noted detection system false alarm responses as another cause eg. due to smoke alarms being activated by dust, or thermal detection circuitry being open-circuited through building structural movement. True and false alarms may be indistinguishable.

Response of fire brigades

Cousins et al (1990) noted that the potential shaking damage to fire stations is significant to the operational availability of fire service vehicles after the earthquake. Other circumstances which have delayed fire brigade response after an earthquake, and as given by Chung (1995), include access routes impassable due to road surface damage, or blockage by collapsed structures or debris, traffic jams, and downed power wires.

Water supplies reduced or exhausted

The lack of water or insufficient pressure due to earthquake damage to underground distribution networks or due to the draining of unprotected reservoirs, are causes given by EERI (1985) which can severely modify normal fire-fighting activities at the fireground.

6.4.3

Strategos Report (1989) suggested that for a typical NZ house the time interval between ignition and the fully-developed fire stage is only 5 - 10 minutes.

For industrial and commercial structures it was suggested that:

- this time interval is more variable than for houses (being typically 5 - 20 minutes)
- the rate of fire spread is affected by the size of the room of fire origin and the flammability of the contents.

In very large structures the time to the fully-developed fire stage could be 60 minutes or longer.

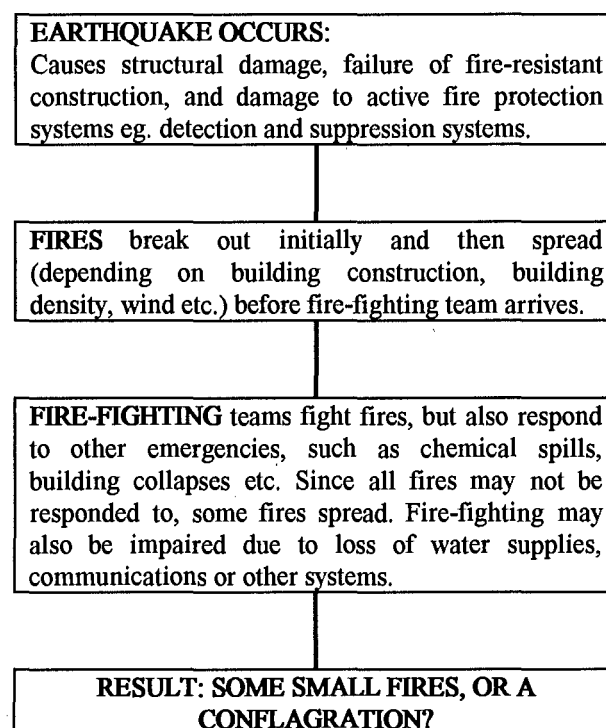
By these predictions, and after a major earthquake, fire brigades may have very little chance of saving any house that ignites, and commercial and industrial buildings are expected to be totally involved with fire by the time the fire brigade arrive, or be heavily involved (depending on the effectiveness of any passive protection acting against fire spread). Large amounts of water and manpower will be required if significant damage prevention is to be achieved.

Therefore, after a major earthquake, and unless a burning commercial or industrial premises has a sprinkler system with stored water on site and diesel engine-powered standby pumps which operate successfully, those large fires may become uncontrolled fires. The over-taxed fire brigade resources may then only be deployed for ensuring evacuation of endangered occupants, and the protection of adjacent exposed buildings in an attempt to prevent fire spread.

6.4.4

The complexity of the post-earthquake fire problem and the involvement of many diverse elements is acknowledged by Scawthorn (1985). It described post-earthquake fire potential in a simplified flowchart, depicted in Figure 6.1.

Figure 6.1: Post-earthquake fire potential



6.5 Substantiation of concepts through historical evidence

6.5.1

Qualitative studies of fifteen selected major earthquake events undertaken in Chapter 5.0 and analysed and reported in a common format in Appendix 2, have provided historical evidence which will be drawn on to substantiate the concepts of how fire protection response following a major earthquake could differ from the response to fires at any other time. The following factors will be examined:

- likelihood of multiple simultaneous ignitions
- fire reporting delays
- fire brigade response delays
- probability of maintaining fire-fighting water supplies.

Likelihood of multiple simultaneous ignitions

Table 6.1 summarises the number of reported initial outbreaks following selected major earthquakes. The data has been extracted from the earthquake reports in Appendix 2. The majority of reports considered the initial outbreaks as being the number of ignitions within the hour following the earthquake, but other reports were less specific and the figures given may have been for periods in excess of one hour post-earthquake.

Table 6.1: Reported post-earthquake initial fire outbreaks

Earthquake event:	Reported post-earthquake initial fire outbreaks:
San Francisco, 1906	50 (all grew quickly to conflagration proportions)
Japan, 1923	134 (all grew quickly to conflagration proportions)
Napier, 1931	3 (started in Chemists' shops; later caused conflagration)
Long Beach, 1933	15 (confined to buildings of fire origin)
Niigata, 1964	9 (one caused conflagration in a residential area)
San Fernando, 1971	116 (3 in broken gas lines in streets)
Managua, 1972	4 - 5 (developed to a conflagration)
Morgan Hill, 1984	3 - 4 (confined to buildings of fire origin)
Mexico City, 1985	Number of initial outbreaks not given, but one reference noted that within 24 hours of the earthquake 200 fires had been reported (confined to buildings of fire origin).
Edgecumbe, 1987	No fires reported.
Whittier Narrows, 1987	Number of initial outbreaks not given, but several references noted that within the first 5 hours 58 structure fires (confined to buildings of fire origin) and 75 gas fires had been reported.
Loma Prieta, 1989	27 in first 2 hours (confined to buildings of fire origin)
Hokkaido Nansei-oki, 1993	Initial fire outbreak immediately developed to a conflagration.
Northridge, 1994	50 structure fires reported in the first 2 hours, and 110 over 6 hours (majority confined to a building of fire origin)
Kobe, 1995	89 fires had started within 14 minutes of the main shock (about 50% developed to conflagration) 205 fires occurred on the first day 240 fires by midnight four days later

Data has also been extracted from the earthquake reports in the Appendix 2 to compare the daily incident reporting rates (fire and other emergencies) of some fire departments under normal circumstances, with the incident reporting rates after major earthquakes, and this is summarised in Table 6.2.

The following conclusions have been made from the data presented in Table 6.1 and Table 6.2:

1. The experience following past major earthquakes has shown that multiple ignitions will occur as a result of major earthquakes and within a short time of the main shock, and may fully extend or overwhelm the response of fire departments. It should be noted that fire departments are the first line of response for a wide range of emergency situations. However, during and following a major disaster, even the best equipped and best trained fire service in the country cannot be expected to maintain adequate staffing and equipment levels to simultaneously respond to all of the emergencies.
2. Fires will either be confined to the building of fire origin, or will spread, and may grow to conflagration proportions depending on the ability of the fire department to control and suppress them. Conflagration potential is discussed in Chapter 8.

Table 6.2: Normal and post-earthquake incident reporting

Earthquake event	Incident reporting rates under normal circumstances (daily average)	Incident reporting rates post-earthquake
San Fernando, February 1971	73 (February daily average for Los Angeles Fire Dept. in 1971)	436 (on day of earthquake)
Morgan Hill, 1984	1.9 (Morgan Hill Fire Dept.)	35 (in nine hours following 'quake)
	96 (San Jose Fire Dept.)	62 (in five hours following 'quake)
Whittier Narrows, 1987	Not given, except report that post-earthquake rate was nearly twice the normal load of Los Angeles Fire Dept	1,185 (on day of earthquake)
Loma Prieta, 1989	Not given for San Francisco Fire Dept	400 (in four hours following 'quake)
Northridge, 1994	900 (Los Angeles Fire Dept. in 1994)	2,200 (on day of earthquake) 1,800 (during the days following)
Kobe, 1995	2.2 (Kobe City Fire Dept. in 1992)	53 (immediately following the main shock)

Fire reporting delays

The data in Table 6.3 has been extracted from the earthquake reports in Appendix 2 to assess whether the factor "fire reporting delays" has proven to be a significant issue to fire protection response following major earthquakes.

The following conclusions have been made from the data in Table 6.3:

1. Following a major earthquake a less than ordinary telephone response should be expected due to an increase in telephone use and the built-in protection of the equipment (in modern networks this may lead to an automatic announcement, or a slow-down in dial tone being received which may be perceived as a telephone outage). Citizens may resort to driving to fire stations to report incidents, and this can cause critical delays to the arrival of emergency assistance.
2. Fire department computer-aided dispatch systems and internal radio communications are under very much greater than normal service demands in responding to emergency aid requests following a major earthquake, and their failure can significantly affect the ability of the fire department to provide an appropriate fire protection response.
3. Telecommunications equipment sites and networks can be exposed to the full severity of a major earthquake and can significantly impact on fire protection response by preventing or delaying the reporting of requests for emergency aid. These sites and networks must be constructed so as not to be vulnerable to earthquake attack and must have a high probability of survival following an extreme event.
4. Perhaps one of the most challenging opportunities for reducing the loss of life and property as the consequence of post-earthquake fire is through ensuring the means of communicating emergencies to the fire service, so that there is a high probability of fire protection response being achieved before incipient fires become fully-developed fires. It is suggested that this is an area where emerging communications technologies may provide significant improvements.

Fire brigade response delays

The data shown in Table 6.4 has been extracted from the earthquake reports in Appendix 2 to establish the nature of, and the extent to which, conditions during and following a major earthquake could affect the activities of fire departments, and hence fire protection response.

At least two key factors were identified as being critical to fire department response and suppression effectiveness:

1. Availability of plant and man-power.
2. Impediments to the access to fire grounds.

The earthquake reports were analysed to establish the extent to which these two factors, were present.

The following conclusions have been made from an analysis of the data in Table 6.4:

1. Fire stations are exposed to earthquake damage, and the potential damage can be significant to the operational availability of fire service staff, vehicles and equipment.
2. There is a vital need for on-going planning and training in fire departments, and increased staffing and upgrading of equipment to achieve appropriate response times to post-earthquake fires, and a suppression effectiveness which will achieve control of

the initial outbreak of fire. This was indicated by the fire department response to the Loma Prieta event.

3. Following a major earthquake impediments to fire department access to fire grounds could be expected due to conditions such as:
 - roads being impassable from fissuring or slumping
 - damaged bridges and tunnels
 - road blockage by flooding, debris or collapsed structures, or downed power wires, or congested by pedestrian and/or vehicular traffic.
4. Given adequate fire-fighting resources, the extent of fire protection response following an earthquake will be influenced by the ease (or lack of difficulty) the fire department has in getting to fire grounds ie. how much equipment can be provided at the firegrounds and how quickly fire-fighter intervention can be provided.
5. As is the case under normal conditions, the extent that fire-fighting activity is successful at an early stage of post-earthquake fire outbreak (ie. the performance of the fire-fighting activity) is a key factor to the amount of fire damage resulting. It is the difference between some small fires and a conflagration.

Table 6.3: Extent of reporting delays due to earthquake damage to communications system

Earthquake event	Reported effect on communications systems	Reported effect on communicating emergencies to fire department
San Francisco, 1906	Telephone system failed over a considerable area. Fire alarm receiving office was wrecked by the earthquake.	Many unsuccessful attempts to send in alarms. Alarms could not be received.
San Fernando, 1971	Parts of the telephone system in the LA area were disrupted due to physical damage, power supply outages, and overloading of telephone circuits. Sylmar CO was severely damaged due to shaking.	The disruptions made contacting the fire department difficult.
Managua, 1972	Local telephone system was disrupted due to equipment damage at main exchange and at several smaller exchanges outside of town.	The fire department could not be contacted.
Morgan Hill, 1984	No significant damage to communications systems but overloading down-graded quality of service.	Imposed delays to the reporting of emergencies to the fire department. Citizens resorted to driving to fire stations to report incidents).
Mexico City, 1985	Telephone system was seriously damaged due to intense earthquake shaking. Main exchange building collapsed and many others were severely damaged	The fire department could not be contacted.
Whittier Narrows, 1987	Telephone system remained serviceable, and Emergency 911 service was operational although saturated with calls.	Not clear to what extent fire protection response was delayed due to the dispatch system and how much was due to difficulties in travelling to the fires.
Loma Prieta, 1989	No mention of state of telephone system, but San Francisco Fire Dept. Despatch Computer was reported to have gone down due to overloading 5 minutes after the earthquake struck. SFFD radio comms. also reported overloaded by operational traffic.	Fire units were manually dispatched until the call volume subsided.
Northridge, 1994	Significant disruption to telephone and other land based communications systems. Potential weaknesses revealed in communications, and some systems suffered damage. LAFD Operations Control Dispatch Centre lost its standby power.	Many citizens unable to report requests for aid by telephone. Necessitated an altered mode of operation. Significant impairment to communications with fire department and degraded emergency response. Computer-aided dispatch capability lost.
Kobe, 1995	Kobe City state-of-the-art Command and Control Centre unable to receive emergency calls immediately after the earthquake due to major damage to telephone equipment and call overloading.	The fire department could not be contacted. Control of operations transferred to fire stations.

Table 6.4: Extent of fire department operational availability and impediments to fire ground access as reported after past major earthquakes

Earthquake event:	Factors which affected the operational availability of brigades.	Factors which affected fireground access by brigades.
San Francisco, 1906	Fire stations were damaged but all fire vehicles went into service.	No reported access problems.
Japan, 1923	Fire stations were damaged preventing the use of some fire vehicles and equipment. Fatalities and injuries were reported: 22 firemen killed (mostly burnt to death) and over 100 were injured.	Access to fires was blocked by collapsed buildings and bridges, and fissured and slumped roads.
Hawkes Bay, 1931	Napier Central Fire Station was destroyed in the earthquake and fire engines were buried.	Rubble blocked streets and downed power lines made access to fires difficult.
Managua, 1972	Three fire stations collapsed on the trucks and other equipment. Some portable equipment was salvaged and used but there was a serious lack of fire-fighting resources.	Narrow streets were blocked with debris, impeding the use of vehicles.
Mexico City, 1985	Fire Department HQ. building was damaged by the earthquake and this caused a delay in organising fire service response.	No reported access problems.
Loma Prieta, 1989	San Francisco Fire Dept. had insufficient reserve apparatus and an aged apparatus fleet, no reserve aerial trucks with operational aerial ladders, inadequate availability of fuel to refuel apparatus, and inadequate supply of nozzles and fittings for reserve apparatus. Internal co-ordination and communications during the critical hours were at times chaotic.	No reported access problems.
Hokkaido Nansei-oki, 1993	The two Aomae FD. fire trucks and other equipment resources were available, but only 11 men (25% of the volunteer force) were available for fire-fighting duties.	Access to seat of fire was blocked by debris in the narrow streets, impeding the use of vehicles. Conflagration followed.
Northridge, 1994	Los Angeles region had a large and well equipped fire service. Sufficient resources were available to deal with all fire ignitions and other emergencies. All earthquake related fires (110) were under control within 5 hours of the earthquake.	No reported access problems.
Kobe, 1995	Kobe City Fire Bureau is a modern and relatively well manned, well trained and equipped fire brigade of 27 stations, over 200 vehicles and 5,300 regular and volunteer staff. Earthquake damage affected fire stations and fire-fighters.	Access to sites was limited by narrow, rubble-strewn streets, also congested with pedestrian and vehicle traffic. Fire spread rapidly through closely spaced wooden houses. Demonstrated the extreme importance of controlling the initial outbreak of fire, especially in areas that are prone to a conflagration risk.

Probability of maintaining fire-fighting water supplies

The extent to which the availability of fire-fighting water supplies is modified by the effects of a major earthquake has been analysed from data extracted from the earthquake reports in Appendix 2, and which is shown in Table 6.5.

The following conclusions have been made from the data in Table 6.5:

1. Past experience has indicated that fire protection response following a major earthquake can be expected to some extent to be impaired by reduced or depleted fire-fighting water supplies. It has shown there is only a low probability of maintaining water systems for fire-fighting response. Of the thirteen events reported only one (Whittier Narrows, 1987) did not result in fire-fighting ability being adversely affected through depletion of water supplies.
2. Underground reticulated water systems are vulnerable to major earthquake shaking and ground faulting even in a moderate earthquake. This is particularly so in areas of fill or infirm soil. Experience has shown that the area of the underground damage to water lines can be much larger in size than the area of above-ground structural damage, and this suggests that pipes are more vulnerable to earthquake damage than buildings.
3. The need for reliable post-earthquake water supplies for rapid fire-fighter intervention and suppression effectiveness has been consistently demonstrated in past major earthquake events, when the likelihood of multiple simultaneous ignitions is great.

Table 6.5: Cause and extent of water supply failures and the effect on fire-fighting activities after major earthquakes

Earthquake event	Reported cause and extent of water supply failure	Reported consequences of water supply failure
San Francisco, 1906	Complete water supply failure in most of the city. Major water transmission lines (3) failed where they crossed marshy ground. Wide-spread damage to the distribution system throughout the city.	Absence of water in burning district seriously disrupted fire dept. response. Fires quickly grew to conflagration proportions, driven by persistent wind and a succession of wind changes.
Japan, 1923	Complete water supply failure occurred.	Reported to be the most important factor contributing to the spread of fire after this earthquake.
Hawkes Bay, 1931	Almost all water pipelines were damaged. Cast iron mains were badly fractured at junctions, and at joints lead packings were disturbed allowing extensive leakage. A hill-top reservoir was badly fractured and a high pressure water tower overturned. Complete water supply failure within an hour of the earthquake. Hastings water supply also failed due to fracturing of the mains across the Havelock bridge.	Napier fire brigade did not have enough water to save many buildings, but managed to obtain a supply from a pumping station and from a salt water sump which allowed the fire-fighters to stop fire spread along three streets.
Long Beach, 1933	Underground watermain breakage occurred particularly in filled ground on the water front.	No other details reported.
Niigata, 1964	Underground pipes including water lines were broken.	No other details reported.
San Fernando, 1971	Water system for City of San Fernando was devastated. Wells were ruptured, reservoirs were cracked. Distribution systems were so fractured that they had to be almost entirely rebuilt. Many pumping stations not structurally damaged were inoperative due to failure of electricity supplies to the pumps. Water was drafted from swimming pools.	No serious spread of fire occurred.
Managua, 1972	Underground piping of water distribution system was badly damaged particularly in poor ground areas and across earthquake faulting. Distribution system consisted of over 600km of piping using materials including ductile iron, cast iron, galvanised iron, asbestos cement and PVC. Many breaks in street mains.	Absence of serviceable water hydrants severely hampered fire-fighting operations and was given as one of the reasons why fires were able to rage uncontrolled through many downtown blocks in the city for over a week after the earthquake.
Morgan Hill, 1984	Large water losses due to breaks in two transit water lines, and numerous water service connection failures in the high damage areas.	Adequate water to contain and suppress the few major fires, but the possibility for the outbreak of fire in residential areas without water supplies for several days was a concern, but no ignitions occurred.

Table 6.5 (continued): Cause and extent of water supply failures and the effect on fire-fighting activities after major earthquakes

Earthquake event	Reported cause and extent of water supply failure	Reported consequences of water supply failure
Mexico City, 1985	Water system pipes were seriously damaged. Area of underground damage to water lines was much larger in size than the area of above-ground structural damage. Damage resulted in the complete loss of water supplies to four suburbs, and severe curtailment in six other suburbs. Water line failures were shear failure (in the large distribution pipes) , and telescopic failures in smaller diameter pipes	Lack of water adversely affected fire-fighting ability.
Whittier Narrows, 1987	Water supplies in the Los Angeles region performed well and there was little disruption to service from damage to transmission or distribution systems. Several dozen watermain breaks and leaks in Whittier, and peak water pressure only at about 50% normal during the two days after the event.	Limited areas were without fire-fighting water for a period of hours, Was reported that fire departments did not have any problems through water supply failures.
Loma Prieta, 1989	Water mains broke throughout the City of San Francisco in areas of filled or infirm soil. The Marina District was severely impacted by 69 breaks in the high pressure water mains and affected the supply to fire hydrants in a 44 square block area. Water was drafted from the harbour by a fireboat and delivered to the fireground six blocks away by means of the Portable Water Supply System (PWSS).	Severely affected fire-fighting operations in the Marina District and in the outlying residential district in the southwest section of the city. Fire was confined to one square city block. Had it not been for the water pumped by the fireboat, the Marina District would have been lost. The fireboat pumped approximately 6.5 million gallons over 18 hours.
Northridge, 1994	Damage to water supplies in the San Francisco Valley area caused water loss from breaks in at least 6 trunk lines and from approximately 3,000 leaks. Pumping stations and storage tanks also sustained damage.	Lack of water pressure at hydrants at many locations in the western and northern parts of San Francisco Valley. The fire-fighting effort depended on the availability of alternative water supplies (eg. swimming pools) to deal with fires in many of the earthquake effected areas.
Kobe, 1995	Underground piping sustained approx. 2,000 breaks which rendered most hydrants unserviceable. Water was drafted from water cisterns, but many older water cisterns across Kobe City were damaged and lost their water. Tankers were used to ferry water to some fire locations, but these could not navigate the narrow streets to all fire sites. Small fire trucks designed for the narrow streets had limited water storage capacity.	The lack of readily available water supplies in Kobe City was a key factor in the rapid fire spread through areas prone to conflagration risk. In neighbouring Osaka and Kyoto Cities the fire departments functioned fairly well by drafting water from cisterns, swimming pools and a river, and could cope with sequential fires.

6.6 Conclusions

6.6.1

This chapter identifies ways in which the fire protection provided in the urban environment is changed in the aftermath of a major earthquake.

6.6.2

The main conclusions are:

1. Under normal circumstances response to building fires will be by a combination of fire protection systems in place in buildings, both active and passive, and the fire brigade summoned to the premises. If automatic sprinkler systems are present they will generally achieve containment of fires at an early stage of fire development, while fire brigades are capable of containing major fires to limit spread. In each case adequate water supplies need to be available.
2. Following a major earthquake, response to in-place fire protection system activations is likely to be disrupted due to any of the following reasons -
 - a). Likelihood of multiple simultaneous ignitions
 - due to insufficient fire brigade resources for the number of fires ignited at the same time by the earthquake, and other non-fire demands on fire brigades, these fires have the opportunity to grow and spread over large areas because they are not responded to.
 - b). Detection delays
 - ignitions may be undetected for a long period of time due to damaged detectors or wiring, or due to distracted observers, resulting in large fires which are more difficult to extinguish.
 - c). Reporting delays
 - may be caused by failure of communications systems through direct external damage, or through overload from high useage levels; the latter may also be due to a large number of false alarms which are indistinguishable from genuine fire alarms).
 - d). Impairment of fire brigade response
 - resulting from shaking damage to fire stations and loss of operational availability of fire service vehicles and equipment after the earthquake
 - due to impassable access routes eg. road surface damage, road blockages by collapsed structures or debris, downed power wires or traffic jams.
 - e). Water supplies reduced or exhausted
 - due to earthquake damage to buried water distribution networks or draining of unprotected reservoirs
 - the need for reliable post-earthquake water supplies for rapid fire-fighter intervention and suppression effectiveness has been consistently demonstrated in past major earthquakes when the likelihood of multiple simultaneous ignitions is great

- it has been shown that there is only a low probability of maintaining water systems for fire-fighting response.

3. After a major earthquake and with the expected rate of fire growth and development of fires in typical NZ residential buildings, fire brigades may have very little chance of saving those that catch fire, when faced with the demands and likely disruptions as noted above. Likewise, unless commercial and industrial buildings have sprinkler systems with stored water and independently powered pumpsets on site, it is expected that if they caught fire they would be heavily or totally involved by the time the fire brigade arrived, depending on the effectiveness of passive fire protection acting against fire spread within the building. Large amounts of water and manpower may be required if significant damage is to be prevented. Overtaxed fire-brigade resources will then most likely only be deployed for ensuring the evacuation of endangered occupants and the protection of adjacent exposed buildings.

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CHAPTER 7.0

POST-EARTHQUAKE FIRE IGNITION SOURCES

7.1 Background

7.1.1

The post-earthquake fire experiences referred to in Section 6.5 have shown that fire loss directly attributable to the earthquake begins immediately following the ground shaking, and can continue for days after the shaking has stopped with fire incidence greatly exceeding the normal rate.

7.1.2

This chapter provides a discussion on the nature of post-earthquake ignition sources as identified in the studies of the fifteen major earthquake events reported in Appendix 2. Scenarios for ignition, and the influence of the restoration of power and gas utilities on post-earthquake fire incidence will be discussed. Fire engineering responses to reduce the effect of ignitions will also be considered.

7.2 Nature of ignition sources

7.2.1

Table 7.1 is a summary of the reported ignition sources following selected major earthquakes. The data has been extracted from the reports in Appendix 2.

Table 7.1: Summary of reported ignition sources following major earthquakes

Earthquake event	Reported ignition sources
San Francisco, 1906	<ol style="list-style-type: none">1. Collapse of buildings containing fires in open fire places. Forced contact between combustibles and lit kerosene lamps and gas lights in dwellings and businesses, and boiler fires in factories.2. Fracturing of internal electrical wiring as the result of structural damage to buildings (the electrical service current was not shut off for some minutes after the initial shock).3. Some crosses of 550 volt tram wires with other wires, and the consequent sparking and arcing of working electrical appliances and circuits in buildings.
Japan, 1923	<ol style="list-style-type: none">1. Large number of heating units, and cooking stoves, in use for midday meals.2. Chemical fires occurred at pharmaceutical and medical colleges, educational establishments, apothecaries, dental clinics and soap factories.
Hawkes Bay, 1931	<p>Fires originated in three chemists' shops; were probably due to the release of fluids and vapours from broken containers, and their ignition by Bunsen burners.</p> <p>The violent emptying of shelves and the breaking of containers, and the spreading and mixing of their contents added to the fire load, and may have caused exothermic chemical reactions which ignited adjacent fuels.</p> <p>Ignitions sources were also reported as broken lights and heating units, and the fracturing of internal electrical wiring, in contact with combustibles..</p>

Table 7.1(continued): Summary of reported ignition sources following major earthquakes

Earthquake event	Reported ignition sources
Niigata, 1964	<ol style="list-style-type: none"> 1. Cooking oil spills ignited by hot surfaces. 2. LPG leakage ignited by a working oven. 3. Spilled chemicals causing exothermic reactions and ignition of adjacent combustibles.
San Fernando, 1971	<ol style="list-style-type: none"> 1. Electrically sourced ignitions due to severed electrical wiring was the cause of some house fires. 2. Ignition of leaking gas from ruptured gas lines caused fires in some mobile homes (after they had been shaken off their foundations). 3. Ignition, by unspecified causes, of leaking gas from some buried gas distribution mains.
Managua, 1972	Not reported (except for arson about two days after the earthquake).
Morgan Hill, 1984	<ol style="list-style-type: none"> 1. Broken natural gas pipes to heating elements in gas appliances caused two fires. 2. Chimney and gas heater flue damage by earthquake shaking caused fires in several residences. 3. Arcs from electrical short circuits and over-heating caused two fires. 4. Grass fires caused by "downed" power lines arcing to ground.
Mexico City, 1985	Major fire caused by ignition of gas leak from storage tank. No other reports.
Whittier Narrows, 1987	<ol style="list-style-type: none"> 1. Arcing and shorting when power was restored to damaged electrical appliances and fallen light fixtures was a general cause of fire. 2. Movement of combustible material towards a heater by earthquake motion resulted in an ignition, and fire. 3. Mixing of spilled chemicals. 4. Grass-land fires caused by burned-down power lines (overhead lines making contact due to earthquake-induced motion, burning through the conductors and causing them to drop).
Loma Prieta, 1989	<p>Shut-down of electric power eliminated this as an ignition source: caused all electrically powered safety valves to close, shutting off the pilot and interrupting gas flow at that point. It is believed this action prevented many ignitions in buildings where there was enough movement to break the internal pipes, and sever the electrical wiring.</p> <p>Actual ignition source of initial fire in the Marina District was not reported. Ignition of spilled solvents caused a major fire in an auto-service building.</p>
Hokkaido Nansai-oki, 1993	Ignition from cooking or heating appliance in residential area likely cause of fire that followed about 14 minutes after earthquake.
Northridge, 1994	<ol style="list-style-type: none"> 1. Natural gas leaks from supply lines to toppled water heaters (and ignited by the gas flame) was the cause of fires in many residences. 2. Hazardous chemical interactions caused a small number of ignitions. 3. Electric arcing as the result of short circuits also caused a number of ignitions. 4. A 10" diameter oil pipeline in a suburban street ruptured and caused a massive spill which was ignited. A wall of flame destroyed two houses and 17 cars before being brought under control. <p>Specific mention of arson not being a major problem. LAFD reported an average daily occurrence in Los Angeles of about 10 cases. There were 11 cases over the three days following the earthquake.</p> <p>Some fires occurring in the days following the earthquake were directly attributable to the restoration of electricity and gas supplies shaken in the initial earthquake and the aftershocks. These fire incidents occurred at greater than normal daily rate in the days following the earthquake.</p>

Table 7.1(continued): Summary of reported ignition sources following major earthquakes

Earthquake event	Reported ignition sources
Kobe, 1995	<p>1. Power lines were either knocked down or torn from collapsed buildings creating potential arcing situations.</p> <p>2. Broken natural gas pipes were found at many of the fire sites, and kerosene heaters were present in the ruins of most buildings, suggesting that gas and flammable liquids such as kerosene could have been accelerants, and fuels, for many fires.</p> <p>3. There were also fires due to suspected arson.</p> <p>The fires which occurred immediately after the earthquake resulted from gas leakages or gas appliance ignitions, other fire appliances, or chemical ignitions. These then decreased as the proportion of electrical ignitions increased in connection with the restoration of electricity supplies to collapsed structures and to damaged appliances, wiring and light fixtures, which ignited combustibles. The rapid restoration of gas and electricity was a significant cause of fresh ignitions. There were also ignitions associated with recovery actions (eg. the use of candles in gas-affected compartments, and fires for warming displaced survivors, getting out of control).</p>

7.2.2

The data in Table 7.1 identifies the primary nature and the particular aspects of post-earthquake ignition sources. The main issues are:

1. Ignition sources - are primarily electrical or gas-related in nature, but could also include open flame, hot surfaces, exothermic chemical reactions from spilled chemicals, and fires intentionally lit.
2. Electrical ignition sources -
 - (i). Earthquake shaking, in causing structural damage can also stress the electrical wiring in a building causing short-circuits, or electrical appliances can be overturned or otherwise disturbed and lighting fixtures dislodged, even in a moderate earthquake. This damage may not pose a risk of ignition from arcing and shorting as long as the electricity is disrupted, but even with circuits de-energised residual heat in many appliances may still cause the ignition of toppled combustible goods which have landed on electrical appliances such as ranges, space heaters, and lighting fixtures.
 - (ii). Toppled combustible goods in contact with damaged electrical appliances may be hazardous if the electricity service is restored before combustibles are removed. This scenario is thought to have been a significant cause of fires following the 1995 Kobe, Japan, earthquake.
 - (iii). Other heavy plant, machinery and equipment may malfunction under strong shaking, creating other ignition sources.
 - (iv). Burned-down power lines, by arcing to ground, can cause fires in gas leaks from gas mains and grass-land fires. The suggested scenario here is overhead lines making contact due to earthquake-induced motion and burning through the conductors, causing them to drop. If the circuit is not tripped (ie. due to a high resistance contact to ground) then arcing to ground may occur, creating the ignition hazard.

3. Gas and flammable liquid ignitions -

(i). While not a source of ignition, gas liberated through earthquake damage to gas appliances, to gas supply lines or gas storage facilities, is ignited by electrical sources, or flames in the appliances themselves.

(ii). In the Northridge post-earthquake situation natural gas leakage ignited by electrical sources fuelled a significant number of fires.

(iii). In the same earthquake a large diameter oil pipeline in a suburban street ruptured and caused a massive spill which ignited. This fire fuelled two house fires and 17 car fires, before being brought under control.

(iv). Fires have been caused through spills of liquid fuels from ruptured heating systems, and from emergency generator power supply day tanks. Chemical spills are other fuels for post-earthquake fires, but they could also be the source of ignitions if exothermic chemical reactions result.

4. Hot surfaces -

(i). Solid fuel burners which run with high surface temperatures can be a source of ignition when in contact with dislodged combustibles, or if the units are insecure and topple during earthquake shaking.

(ii) The movement of combustible material towards a heater by earthquake motion resulted in an ignition and fire after the Whittier Narrows, 1987, event.

5. Open flame -

(i). The over-turning of heat sources such as solid fuel stoves, kerosene lamps, heaters, cookers and braziers can spread open flame into adjacent combustibles.

6. Incendiarism -

(i). Suspected cases of arson occurred after Kobe.

(ii). Specific mention of arson after Northridge not being a major problem.

7.3 Effect of restoration of gas and electricity supplies on ignitions

7.3.1

Data in Table 7.1 indicates that the restoration of electricity and gas supplies, shaken in the initial earthquake and the aftershocks, was the cause of some of the fires occurring in the days following the Northridge and Kobe earthquakes. These fire incidents occurred at greater than normal daily fire incident rates. Most were caused by the restoration of power to buildings damaged in the earthquakes, and were due to the re-energisation of damaged appliances, wiring or lighting fixtures and the subsequent ignition of combustibles in contact. Leaking gas was also ignited and caused additional fires.

7.3.2

According to Todd (1994) the restoration of gas and electricity supplies places at odds the desire to restore utility services as quickly as possible and the desire not to cause additional fires.

After the Kobe earthquake there did not appear to have been close liaison between gas and electricity suppliers and the emergency rescue and recovery services, before supplies were restored.

NZNSEE (1995) acknowledged, as did other reports, that the rapid re-instatement was a significant cause of fresh ignitions, and provided a time-line for the restoration of electricity services as follows:

- two hours after the earthquake about 1 million customers were without power (out of 11.7 million customers supplied by the company)
- within 8 hours supply was restored to 50% of these
- within 3 days to 90%.

Within 5 days supplies were restored to virtually all customers requiring power.

Means of limiting ignitions during the re-instatement of electricity and gas supplies were identified in Chung (1996) in terms of the following strategies (and which in part consolidates the above discussion):

- re-energisation of an earthquake damaged area needs to be co-ordinated between the different utilities and the emergency rescue and recovery services
- prior to restoration of electrical service, techniques or instrumentation needs to be developed to ensure that electricity is not restored to damaged structures or areas with natural gas leaks.

EARTHQUAKE SPECTRA (May 1985) had earlier suggested that strategies for service restoration should include:

- restoring service only after individuals are present in every structure, with public officials authorised to enter structures where owners are absent, in order to check for fire, or gas leaks
- fire units should stand by in the area at the time of utility restoration.

7.4 Fire engineering responses to reduce the effects of ignitions

7.4.1

Overall post-earthquake fire objectives, according to Chung (1995), should be:

- to reduce the number of ignitions, and
- to reduce the likelihood that fires will spread.

7.4.2

Kenna (1975) suggested it is not possible to eliminate all initial, or incipient, outbreaks but that the risk of these may be reduced by some measures (eg. by some installation procedures accorded to heaters, stoves, fuel lines and fuel tanks etc, and the installation of seismic cut-off valves actuated by seismic shock for the rapid shutting-off of gas supplies).

In terms of the hazard of incipient outbreaks, Kenna considered that provided they can be contained, or extinguished, before spread of fire occurs they do not represent a serious hazard.

Chapter 3 described the role of passive fire safety systems as that of containing incipient outbreak and the spread of fire itself, or the spread of products of fire, to within the firecell.

Extinguishment will be by suppression activities, or due to exhaustion of the fuel in the firecell. Chung (1995) acknowledged that suppression activities could be either by automatic fire suppression eg. fire sprinkler systems, or by manual suppression means eg. first stage fire-fighting by building occupants, or through fire brigade response.

In Chapter 6.0 it has been acknowledged that earthquake shaking can cause structural damage leading to the failure of the fire-resistant construction provided by passive fire safety systems, and damage to active fire protection systems eg. to the automatic detection and suppression in the building. Accordingly, a reduction in the effectiveness or availability of active and passive fire safety systems to control the spread of fire from initial ignitions, can be expected to some extent after a major earthquake.

7.5 Conclusions

7.5.1

This chapter discusses the nature of post-earthquake ignition sources and engineering responses to reduce their effect.

7.5.2

The main conclusions are:

1. It is not possible to eliminate all initial, or incipient, fire outbreaks following a major earthquake, but the risk of these may be reduced by some fire preventative practices and installation procedures. The overall post-earthquake fire objectives should be to reduce the number of ignitions, and to reduce the likelihood that fires will spread.
2. Post earthquake ignition sources are primarily electrical or gas-related in nature, but also include open flame, hot surfaces, exothermic chemical reactions from spilled chemicals, and fires intentionally lit.
3. Structural damage caused by earthquake shaking can stress electrical wiring in buildings causing short-circuits, and pose a risk of ignition from arcing and shorting if in-built electrical protection fails to de-energise circuits.
4. Earthquake damage to gas appliances, or gas supply lines, or gas storage facilities can liberate gas which is ignited by electrical sources, or flames in the appliances themselves.
5. Electrical appliances such as cookers, gas-fuelled water heaters and solid fuel burners which are insufficiently restrained can topple or shift sideways, and their residual heat may initiate fires in combustible materials brought in contact with their hot surfaces.
6. Heavy plant, machinery and equipment may malfunction under strong shaking creating other ignition sources.
7. Power lines making contact due to earthquake-induced motion may burn through causing them to drop, arc to ground, and if in-built electrical protection fails to de-energise circuits then further arcing may cause fires eg. in leaks from gas mains, or in dry combustible vegetation etc.

8. Restoration of electricity and gas supplies to damaged appliances, wiring or lighting fixtures can cause ignition of combustibles in contact, and ignition of leaking gas. Means of limiting ignitions during re-instatement of supplies would include -
- co-ordination between the different utilities and the emergency rescue and recovery services
 - supervision of the restoration process on an individual building basis, either by the owner, or in the absence of the owner by a public official authorised to enter the premises and to check for gas leaks and fire.
 - fire units on stand-by in the area at the time of utility restoration.
9. The risk of incipient outbreaks may be reduced by some installation procedures accorded to heaters, stoves, fuel lines and fuel tanks etc, and the installation of seismic cut-off valves actuated by seismic shock.
10. Earthquake shaking can cause structural damage leading to the failure of fire separations and damage to automatic detection and suppression systems in buildings. Therefore, a reduction in the effectiveness or availability of active and passive fire safety systems to control the spread of fire from initial ignitions can be expected to some extent after a major earthquake.

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CHAPTER 8.0

POST-EARTHQUAKE FIRE SPREAD MECHANISMS

8.1 Background

8.1.1

The difficulty of eliminating all initial or incipient outbreaks of fire following earthquake has been acknowledged in Chapter 7. In terms of the hazard of incipient outbreaks, it has been suggested that provided these can be contained or extinguished before spread of fire occurs they do not represent a serious hazard.

8.1.2

To understand the hazard of incipient outbreaks of fire the mechanisms of fire spread will be discussed with particular reference to fire spread within earthquake-damaged buildings and between buildings. Conditions which give rise to conflagration will be considered. Information will be introduced from reports of selected major earthquakes to substantiate and to illustrate the basic concepts of fire spread. Fire engineering measures to reduce the potential for fire spread within and between buildings will also be identified.

8.2 Earthquake damage effects on buildings and the spread of fire.

8.2.1

The structural and non-structural damage caused by earthquakes can, according to EERI (1985), lead to the loss of integrity of many of the fire safeguards generally relied upon, such as firewalls, smoke-control elements, fire-rated roof linings, and wall coverings eg. stucco, brick veneers, and wall linings.

Scawthorn (1992) suggested that in general the damage sustained to the structures of strongly shaken buildings would include cracked walls, broken windows, buckled fire doors and elevator doors, and broken HVAC ducting. The openings created in an earthquake-damaged building can permit the increased ventilation of compartment fires, and enhance fire spread by allowing the uncontrolled migration of smoke and hot gases internally to other areas of a building.

In high-rise buildings even small breaches in the compartmentisation have the potential for permitting large fire spreads. Scawthorn suggested that fire departments will probably not aggressively pursue fires in structurally damaged high-rise buildings (especially where entry is not prudent) because of the large demand for fire-fighting personnel which, generally, an active commitment to fire suppression would require. The only feasible approach (when post-earthquake multiple simultaneous ignitions and other incidents may be placing huge demands on fire departments) will be to ensure evacuation of endangered personnel, to protect adjacent exposed buildings, and to attempt to prevent conflagration (if the water system is not damaged).

Reinforced concrete and steel framed multi-storey buildings are likely to exhibit good post-earthquake stability under fire attack, but according to NZNSEE (1995) fire will

spread through such buildings unless active suppression systems remain operational after the earthquake.

Scawthorn (1992) cautioned that sprinklering of the high-rise may not prevent ignition of parts of the building, since the hydraulic capacity of the system may be overwhelmed if sprinklers are set off on several floors.

8.3 Conflagration

8.3.1

“Conflagration” was defined in Steinbrugge (1982) as uncontrolled fire burning large areas for days.

“Conflagration potential” is the propensity of an urban area to burn. As defined in Oppenheim (1984) it is considered to be the single most important factor governing post-earthquake fire loss. Oppenheim noted that urban areas fall into one of the following classifications:

1. As an area with minimal conflagration potential and where -
 - earthquake-induced fire losses are likely to remain low
 - it is not likely that engineered improvements for fire suppression would be needed.
2. As an area with an intermediate conflagration potential and where -
 - the presence of fire suppression services may be of marked significance
 - the performance of water supplies may control the resulting loss.
3. As an area with high conflagration potential and where -
 - earthquake-induced fire losses are likely to be very high
 - it is not likely that engineering improvements for fire suppression would reduce those losses.

Conflagration potential of certain urban areas may fluctuate seasonally from very low to very high, as a function of humidity, temperature and vegetation.

According to Kenna (1975) additional hazards are provided through the release of flammable gases or spills of combustible liquids used for heating or cooking, as the result of earthquake shaking.

In areas with high conflagration potential Oppenheim considered that earthquake-induced fire losses could be reduced in the long term by either:

- planning (zoning) actions, or
- by the development of strategies eg. firebreaks, to control the almost certain conflagration.

Conflagration-prone areas were characterised, judgementally, in EERI (1985) as those having the following:

- highly combustible, closely spaced structures (especially if a significant number of wood shake roofs are present)
- predominant hot / dry seasonal climates, especially if combined with high winds (as in Southern California)
- forest fire exposure
- poor water supply.

EERI suggested that certain US urban areas may, possibly, be characterised by very low (or minimal) conflagration potential, and that post-earthquake fires ignitions will not spread. Other US urban areas may be characterised by very high conflagration potential, implying major property and potential life loss. EERI concluded that:

- areas of increased potential fire spread are, in fact, more dependent on their fire services than neighbouring areas with less potential fire spread
- as an earthquake impairs fire-fighting services, the one area will be far more influenced than the other.

8.3.2

Three primary means of fire spread in conflagrations were identified in Chung (1996) as being:

1. Flame spread over a continuous fuel surface or array ie. direct flame impingement on the fuel.
2. Ignition of adjacent fuel by thermal radiation from flames.
3. Spot ignitions started down-wind of the main fire by burning brands and embers.

For fire to spread by flame impingement, the flames must be in contact with unburned fuel ie. the fire can only spread along a continuous fuel chain. According to NIST in earthquake-damaged areas continuous fuel chains may be provided by means of collapsed structures leaving combustible debris next to adjacent structures. In some cases the structures may collapse across streets providing a path for fire spread from one block to another.

Mehaffy & Richardson (1994) noted that in conflagrations, fire can spread from building to building whether the structures are timber-framed or reinforced concrete, but that experience has shown buildings constructed of timber structural members and timber exterior components may sustain damage and collapse in an earthquake. They also acknowledged that the resultant rubble would foster rapid fire spread once fire commenced.

However, another view in terms of the speed of fire spread, had been taken in Chung (1996), it being considered that due to under-ventilated conditions the heat release rate of a collapsed wooden structure is less than that of the structure prior to collapse, and hence minimised the flame spread by radiation due to the reduced intensity of the radiation on the target fuel.

The effect of wind is to extend the flame and increase its impingement on the fuel, and to loft burning brands and embers greater distances.

8.4 Mechanisms of fire spread following major earthquakes

8.4.1

Table 8.1 is a summary of the reported fire spread mechanisms following selected major earthquakes. The data has been extracted from the reports in Appendix 2.

Table 8.1: Summary of reported fire spread mechanisms following major earthquakes

Earthquake event	Reported fire spread mechanisms
San Francisco, 1906	<p>Conflagration was severe, and 3 primary means of fire spread were present:</p> <ol style="list-style-type: none"> 1. Direct flame impingement on the fuel. 2. Ignition of adjacent fuels by thermal radiation from flames. 3. Spot ignitions by burning brands and embers. <p>Timber frame buildings were very common in the city (90%), were of considerable height (4 or 5 stories were common) and were located in compact blocks of dwellings. The frame feature greatly facilitated the rapid fire spread. Steady wind and successive wind direction changes drove the conflagration, and maximised its devastation through approx. 28,000 buildings over an area in excess of 10 sq.km.</p>
Japan, 1923	<p>Conflagration was severe, with rapid fire spread through closely spaced dwellings of highly combustible construction. Steady wind and successive wind direction changes during the 8 hour period following the earthquake resulted in approx. 450,000 houses destroyed over an area of approx. 38sq. km.</p>
Hawkes Bay, 1931	<p>Major conflagration which burnt out 10 acres of city buildings. Fire spread was by flame extension from wind-borne fire, by direct flame impingement and by lofted fire brands.</p>
Niigata, 1964	<p>Conflagration through some residential areas was promoted by typical high-density housing, by the combustibility of the materials of their construction, and by narrow streets. Burning oil slick on tsunami-driven waters engulfed some urban coastal buildings but was an unusual element in fire spread by conflagration. Flood waters in other areas limited the extent of fire spread.</p>
San Fernando, 1971	<p>No serious spread of fire reported.</p>
Managua, 1972	<p>Conflagration in downtown areas raged virtually uncontrolled for up to a week following the earthquake. Fire spread was eventually prevented by created firebreaks, and through continued fire-fighting. A number of modern high-rise reinforced concrete buildings exhibited good post-earthquake fire stability but were burned out completely with fires spreading quickly from storey to storey through earthquake-damaged fire-resistive enclosures around stairs and elevator shaft walls.</p>
Morgan Hill, 1984	<p>Fire spread between structures reported due to flying brands (peak wind speed almost 16 mph), and the ignition of a wood shake roof of a dwelling approx. one block downwind from a shopping centre fire.</p>
Mexico City, 1985	<p>No major conflagrations due to absence of wooden buildings and favourable climatic conditions. No buried pipelines of reticulated gas to cause extensive explosions (tank storage only). Leaking gas tank in one hotel building caused a fire which spread into two adjacent buildings.</p>
Whittier Narrows, 1987	<p>No reported fire spread beyond the structures of fire origin.</p>
Loma Prieta, 1989	<p>Radiant heat from apartment building fires in the Marina District was the cause of fire spread to adjacent buildings. There was little wind following the earthquake, and rainfall immediately prior to the earthquake had resulted in high moisture in the ground and wild lands. It was considered possible had there been a wind, that the Marina District fire could have developed into a multi-block conflagration.</p>

Table 8.1 (continued): Summary of reported fire spread mechanisms following major earthquakes

Earthquake event	Reported fire spread mechanisms
Hokkaido Nansei-oki, 1993	<p>Conflagration through the waterfront residential / industrial area. The principal mechanisms of building-to-building fire spread were:</p> <ul style="list-style-type: none"> • ignition of exterior wood trim • radiant ignition of combustible contents through windows • fire spread along scrap wood between buildings • burning kerosene and propane tanks adjacent to building exteriors. <p>Significant quantities of burning wood and embers were flying through the air by wind gusts up to about 5 m/s, but this was reported to not have played a major role in fire spread because most of the buildings had metal rooves, and there were no roof vents through which brands could enter attics. Fire progressed relatively slowly at an estimated 35 m/hour.</p>
Northridge, 1994	<p>Most building fires were confined to the building of fire origin due to a combination of factors, given as:</p> <ul style="list-style-type: none"> • light winds and favourable humidity and time of day (early morning) • building construction • building separation • actions of the fire department. <p>At three mobile home estate fires, building-to-building fire spread was primarily through windows by thermal radiation. Once a unit became completely involved in fire the thermal radiation was sufficient to cause the breakage of windows in an adjacent unit, or to ignite combustibles within the unit directly through the windows. Conflagration did not develop. Fire spread was stopped either by separations such as roads or open spaces, or by fire-fighting operations.</p>
Kobe, 1995	<p>Severe conflagration developed.</p> <p>Fire spread was predominantly by direct flame impingement on continuous fuel chains which were prevalent in the earthquake-damaged areas. These were provided by the predominantly two-storey wooden structures (with heavy ceramic tile rooves) collapsing into piles of debris that included thin dry wood with large exposed surface areas. Many also had highly flammable contents (being industrial occupancies containing solvents and plastics). These provided paths for fire spread between buildings and across roads.</p> <p>Automobiles parked in narrow alleys and in parking lots also helped to spread fire from one block to another.</p> <p>Fire spread was relatively slow as wind velocities during the three days following the earthquake were low, hence fire spread by burning brands or embers was not an issue. The worst affected area was Nagata Ward where about 160 acres, containing approximately 69,000 buildings, was consumed. Many buildings with non-combustible exteriors were destroyed by fire due to flames from surrounding burning buildings penetrating openings eg. windows. Clusters of fire-resistive buildings, with non-combustible exteriors served to prevent fire spread as fire spread from one fire resistive building to another was not evident.</p>

8.4.2

The information concerning post-earthquake fire spread mechanisms, as summarised in Table 8.1, suggests the following:

1. In some earthquake prone areas there is an extreme potential for conflagration to follow major earthquakes.

2. Very high fire losses were narrowly avoided in some other events through water supplies and fire suppression response being available, albeit of marginal adequacy, together with favourable climatic conditions.
3. Growth and spread of conflagrations are a function of -
 - building materials in use
 - urban building densities
 - street widths
 - wind velocities
 - the extent of availability of fire-fighting water at fire sites, and the fire suppression response provided.
4. Control of high conflagration potential in earthquake prone areas is not likely to be achieved, singularly, by improvements in fire suppression strategies but will require more wide-ranging strategies including the following:
 - town planning for increased separation distances between buildings, wider roads (as fire breaks and for improved egress and emergency access), and open spaces (parks and town belts)
 - higher level of fire-resistance in building exteriors, especially in the protection of openings.

8.5 Fire engineering measures to reduce the potential for post-earthquake fire spread within and between buildings

8.5.1

To limit fire spread within buildings by passive means.

Although structural and non-structural damage caused by earthquakes can lead to the loss of the integrity of fire safeguards within a building, it could be expected that the overall effects of this are significantly reduced if the building has been provided with passive fire safety features to limit the horizontal and vertical spread of smoke and fire.

As set out in Buchanan (1995) these fire safety features should include:

- compartmentation, by -
 - fire resistance to walls and floors
 - smoke-control / fire-rated doors
 - smoke / fire barriers in vertical shafts
 - through-penetration fire stopping
 - smoke control / fire-rated dampers in ducts
- fire-rated partitions in ceiling spaces and other concealed spaces
- size and geometry of external windows limited.

8.5.2

To limit fire spread within buildings by active suppression

In the event of fire outbreak and in the absence of fire brigade services, or should fire brigade attendance be delayed, automatic fire suppression eg fire sprinkler or total gas flooding systems can limit the effects of fire to the room of fire origin. To ensure the full serviceability of the suppression system in the post-earthquake fire situation elements of

the system should have appropriate seismic capacity to survive earthquake shaking (this issue is considered in Chapter 9).

8.5.3

To prevent fire spread to other buildings

A principal fire protection feature should be to prevent fire spread to other buildings, and measures to reduce fire spread become important when a fire has become established, particularly in the absence of fire brigade services.

As set out in Buchanan (1995) these fire safety features should include:

- limit the size of windows and type of glazing
- provide adequate separation distances (from adjacent buildings)
- check stability of external walls (to ensure their structural integrity under fire attack).

8.6 Conclusions

8.6.1

This chapter discusses fire spread within earthquake damaged buildings and between buildings. The elements causing conflagration are also identified.

8.6.2

The main conclusions are:

1. The structural and non-structural damage caused to buildings by earthquakes can lead to the loss of integrity of many of the active and passive protection systems generally relied upon. Passive systems such as firewalls and fire doors, smoke-control elements, fire-rated roof linings, wall coverings and linings etc. can be damaged by cracking, buckling or breaking, and the openings created can permit the increased ventilation of compartment fires. They also allow uncontrolled migration of smoke and hot gases internally to other areas of a building.
2. Automatic fire suppression can limit the effects of fire to the fire compartment, but to ensure full serviceability of the system in the post-earthquake fire situation elements of the system should have appropriate seismic capacity to survive earthquake shaking.
3. In high-rise buildings even small breaches in compartmentation have the potential for permitting large fire spreads. This should be resisted by effective passive fire protection as even sprinklering of high-rise buildings may not prevent ignition of parts of the building, due to the possibility of the hydraulic capacity of the system being overwhelmed if sprinklers are set off on several floors as the result of fire spread.
4. Prevention of fire spread to other buildings is a principal fire protection objective. Measures to reduce inter-building fire spread include providing adequate separation distances, limiting the size of windows and ensuring the stability of structural walls under fire attack.
5. Conflagration is the propensity of an urban area to burn. The combustible nature, density and closely spaced dwellings typical of Japanese urban areas and of most cities in the United States, especially in the Cities of Los Angeles and San Francisco, have

by past post-earthquake fire events demonstrated the potential for conflagration and very high losses. These areas in the United States can also be characterised by predominant hot and dry seasonal climates especially if combined with high winds, and poor water supplies. Conflagration prone areas will have a higher dependence on public fire-fighting services than neighbouring areas with a lesser potential for fire spread, and hence the impairment of the fire brigade by earthquake effects will have a greater influence on the post-earthquake fire losses.

6. Fire spread in a conflagration is by three primary means ie. flame spread over continuous fuel surfaces, ignition of adjacent fuels by thermal radiation from flames, and spot ignitions started downwind by burning brands and embers. The effect of wind is to extend the flames and increase their impingement on the fuels, and to increase the distance that burning brands are lofted. Past earthquake events have shown that climatic conditions, and wind speed and direction, can greatly influence the extent of losses from fire in conflagration-prone areas.

CHAPTER 9.0

POST-EARTHQUAKE CONDITION OF BUILDING FIRE PROTECTION SYSTEMS

9.1 Background

9.1.1

If a fire occurs after an earthquake, the earliest detection of incipient ignition and the activation of automatic suppression systems is of utmost importance to:

- giving occupants adequate time to reach a safe place without being overcome by the effects of fire
- minimising fire losses
- ensuring that minimum manpower and equipment is needed to extinguish the fire.

The need for fire detection and suppression systems to remain functional after an earthquake is therefore vital.

9.1.2

Fire detection elements, alarm systems and suppression systems may or may not function properly, following strong shaking. The reporting of damage to detection and suppression systems due to earthquake shaking is an aspect which does not appear to have been widely addressed.

Such commentary following major earthquakes appears to have been confined almost exclusively to the effects of shaking on building sprinkler systems. This emphasis in reporting may have resulted from the recurring evidence that makes apparent over recent years the failure of city water supplies due to severe earthquake shaking, and the high probability for the impairment of fire department response.

9.1.3

This chapter will provide information on the post-earthquake condition of building fire protection systems from the reports of selected recent earthquakes, to substantiate the need for fire detection and suppression systems to remain functional after an earthquake. The extent that NZ Standards have allowed for the seismic design of fire protection systems will be discussed in Chapter 12.

9.2 Reported earthquake damage to building fire protection systems

9.2.1

Table 9.1 is a summary of reported damage to fire protection systems, extracted from the reports in Appendix 2. This information suggests that:

1. Although the vulnerability of building sprinkler systems to earthquake shaking has reduced in recent times with the development of standards for the effective seismic design of systems, inadequate interpretation of the requirements can result in major sprinkler system failures (eg. Edgecumbe earthquake, 1987).

2. Sprinkler heads continue to be extremely vulnerable to damage, and hence to potential leakage, in circumstances of physical impact such as where building elements through which they pass eg. drop ceilings move independently of the heads (eg. Northridge earthquake, 1994)
3. Sprinkler systems are rendered useless when water supplies fail, and building waterway systems, such as dry risers, can be similarly impacted by building structural damage (eg. Kobe earthquake, 1995).

Table 9.1: Summary of reported earthquake damage to building fire protection systems

Earthquake event:	Reported earthquake damage to building fire protection systems:
San Francisco, 1906	Water supplies to sprinkler systems were disrupted by distribution pipe damage.
Japan, 1923	No information located.
Hawkes Bay, 1931	No information located.
Long Beach, 1937	<p>No information on damage to detection or alarm systems, but this was said to be the first major instance of reported performance of sprinkler systems during an earthquake. Lead to the development in the US of earthquake bracing standards for tanks and pipes.</p> <p>Board of Fire Underwriters of the Pacific reported that:</p> <ul style="list-style-type: none"> • probably 500 sprinklered properties were in the earthquake effected area • at least 150 sprinkler systems were subjected to severe strain by reason of location in the immediate area of severe structural damage • predicted that about 80% of these systems would have been able to cope with normal fire occurring in the buildings under protection • within 72 hours about 90% of all risks were returned to almost normal operating condition by means of temporary repairs • about 20% of systems subjected to severe strain had to be completely shut down due to broken mains risers, principal water supplies shut off or destroyed, or due to extensive structural damage.
Niigata, 1964	No information located.
San Fernando, 1971	<p>No information on damage to detection or alarm systems, but it was noted this earthquake provided significant examples of sprinkler system performance, described as follows:</p> <ul style="list-style-type: none"> • levels of building damage and sprinkler system damage related closely • inspections identified about 38 of 973 sprinklered risks (ie. approx. 4%) in the earthquake-damaged area suffered damage ranging from slight to severe, and about 28 (ie. approx. 3%) leaked water • 100 sprinkler installations required repairs by private contractors and the majority involved minor defects (slight leaks, broken hangers and sway braces etc).
Managua, 1972	No information located.
Morgan Hill, 1984	<p>No information on damage to detection or alarm systems, but some damage to sprinkler systems reported as follows:</p> <ul style="list-style-type: none"> • hangers failed, causing piping to break at couplings • piping impacted by other falling services.
Mexico City, 1985	No information located.

Table 9.1 (continued): Summary of reported earthquake damage to building fire protection systems

Earthquake event:	Reported earthquake damage to building fire protection systems:
Edgecumbe, 1987	<p>No information on damage to detection or alarm systems, but severe damage to sprinkler systems in many earthquake-damaged buildings was reported:</p> <ul style="list-style-type: none"> • severity of damage was a consequence of design-related deficiencies in the pipe runs and the fixings (eg. lack of adequate sway bracing, rupturing of piping where differential movement could occur between respective parts of buildings to which it was attached, screwed joints in medium weight pipes also leading to the failure of range pipes) • resulted in pipes and fittings falling to the ground • underground piping of sprinkler water supplies, which included asbestos-cement pipes, failed in shear due to their inherent brittleness (steel pipe and PVC pipe generally behaved well). <p>Although all severely damaged systems were designed to NZS 4541P: 1972 (except for 3 or 4 which pre-dated the publication of that standard), the high level of damage was claimed to be due to inadequate interpretation of the requirement for effective seismic design.</p>
Whittier Narrows, 1987	<p>No information on damage to detection or alarm systems, but several structures had leaking fire sprinkler systems. Some were due to knocked sprinkler heads which operated, while others had leaking pipes.</p>
Loma Prieta, 1989	<p>Private fire protection systems such as sprinklers, standpipes, and alarm systems for the most part were not interrupted. Reported to be probably due to :</p> <ul style="list-style-type: none"> • earthquake bracing requirements included in the fire protection standards governing the installation of these devices in earthquake zones • most of the buildings where such equipment was involved did not suffer extensive structural damage. <p>Several water mains supplying building sprinkler systems were broken in areas of infirm soil.</p>
Hokkaido Nansei-oki, 1993	No information located.
Northridge, 1994	<p>No information on damage to detection or alarm systems, but many sprinkler systems in buildings in the earthquake area remained intact, particularly those installed in accordance with the latest seismic standards applicable. Where damage occurred, it included:</p> <ul style="list-style-type: none"> • broken pipes due to differential building movement or to the sway generated in long pipe runs without adequate bracing • shearing-off at ceiling level of pendant heads where they were supplied from above-ceiling piping • pendant sprinklers pulled through drop-ceilings by the upward movement of pipes, and new holes punched in the ceiling during the downward movement, resulting in damaged sprinkler head deflectors (which would have modified spray patterns and downgraded sprinkler performance).
Kobe, 1995	<p>No information on damage to detection or alarm systems, but it was noted that active building systems were not a factor in mitigating the fires during this disaster:</p> <ul style="list-style-type: none"> • majority of suppression systems were rendered useless by lack of water, due to broken supply piping. • many standpipe connections (ie. dry riser systems) had broken free of the building system.

9.2.2

According to Buchanan (1995), the probability of all active systems working after a major earthquake is remote, due to the likelihood of power failure, water supply failure and structural and non-structural damage.

Many buildings damaged by the Edgecumbe 1987 earthquake remained standing. However, Voss (1987) noted that the sprinkler systems within them did not, generally, remain intact. He predicted that had fire broken out within these buildings it may not have been controlled by the fire sprinkler system, and the final damage bill would have been much greater.

Sprinkler systems are recognised as the principal means of protecting both life and property in large or tall buildings. Unfortunately many sprinkler systems are dependent for water supply on either street mains or electric driven pumps. M & M (1991) cautioned that both are expected to fail in an earthquake, even though, if installed to current codes, the sprinkler pipework itself would survive.

Lifelines (1997) also acknowledged that fire-fighting in high rise buildings may be affected by power failure if the booster pumps supplying pressure to the upper storey sprinkler systems have no auxiliary power supply. Also, damage to the city reticulation itself could leave viable sprinkler systems unable to operate, unless the building has its own water storage. Backup power or water storage are not compulsory and vulnerability therefore varies from building to building.

Earlier Steinbrugge (1982) had stressed the importance of an on-site water supply to ensure the availability of water for sprinkler systems in the event of loss of town main water supplies.

In 1989 Strategos Report noted that in Los Angeles, where there is a recognised earthquake risk, it is a requirement that sprinkler systems in buildings above 23m high incorporate an inbuilt water supply in the building which may be an elevated tank or a pressure tank.

M & M (1991) later noted that in California there was an increasing move towards requiring large buildings to incorporate a stored water tank with diesel engine driven pumps.

Although no serious fires occurred in high-rise buildings after the Loma Prieta 1989 earthquake, Scawthorn (1992) noted that several buildings suffered major sprinkler failures which lead to significant water releases and caused substantial damage. Had fires occurred these systems could have been ineffective or only partially functional, and buildings could have been lost.

Steinbrugge (1982) also commented on the problem of water releases, and the potential losses from water damage to building contents as a result of broken sprinkler piping. Sprinkler systems are obviously supported by the building in which they are placed, and the earthquake bracing cannot be better than the structural integrity of the building. He noted that this implicitly means water damage from broken sprinkler systems remains a constant threat in certain building types, and that a building designed with seismic restraint of sprinkler pipes may still have sprinkler leakage damage after the earthquake.

The possible condition of fire protection systems following an earthquake was discussed by Scawthorn. He noted that in many cases the installed detection, alarm, and suppression systems may be unreliable following a strong shaking because of the following factors:

- dust raised by shaking will often activate smoke detectors so that dozens of alarms may be received simultaneously over a number of floors of a building
- shaking may dislodge detectors or otherwise damage their circuitry so that they cannot function
- this problem extends to building central fire alarm panels, which may not be seismically safe or even properly mounted and therefore could be dislodged, or fall, from their mountings
- the seismic qualifications of the panel interiors may also need to be addressed for unrestrained circuit boards and other components which may also become dislodged under strong shaking.

9.3 Conclusions

9.3.1

This chapter draws on information from reports of the post-earthquake condition of building fire protection systems to substantiate the need for fire detection and suppression systems to remain functional after an earthquake.

9.3.2

The main conclusions are:

1. The probability of all active fire protection systems working after a major earthquake is remote due to the likelihood of structural and non-structural building damage, water supply failure and power supply failure. On-site water storage or backup power for booster pumps are not compulsory and vulnerability therefore varies from building to building.
2. In many cases the installed detection, alarm, and suppression systems may be unreliable following strong shaking because of a number of factors including the activation of smoke detectors over a wide area due to the dust raised by shaking, or the dislodgement of detectors or control panels, or damage to their circuitry, or to the fire alarm wiring through structural damage.
3. Although the vulnerability of building sprinkler systems to earthquake shaking has reduced in recent times with the development of standards for the effective seismic design of systems, inadequate interpretation of the requirements can result in major sprinkler system damage eg. as seen after the Edgecumbe earthquake.
4. The earliest detection of incipient ignition after an earthquake, and the activation of automatic suppression systems, are of vital importance to giving occupants adequate time to reach a safe place without being overcome by the effects of fire, for minimising property losses, and for ensuring the minimum manpower, water and equipment is needed to extinguish the fire.

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CHAPTER 10

POST-EARTHQUAKE WATER SUPPLY SYSTEMS FOR FIRE PROTECTION

10.1 Background

10.1.1

The need for reliable post-earthquake water supplies for fire protection has been demonstrated in past earthquakes. Following an earthquake, public water distribution systems are commonly disrupted. This can be a most important factor contributing to the spread of fire and alternative water supplies may need to be relied upon to provide water for fire-fighting.

10.1.2

This chapter provides an explanation of the nature of typical public water supply systems, how they may be affected by earthquakes, and their role in post-earthquake fire protection in the built environment. Information will be introduced from the reports of selected recent earthquakes to indicate the observed effects on public water supply systems and on fire-fighting tactics. Reference will also be made to the possible effects of earthquakes on the Greater Wellington and Christchurch City and urban water supply lines. A technique and system for the sourcing and delivery of fire-fighting water from alternative water supplies will be reviewed.

10.2 Public water supply systems

10.2.1

According to Scawthorn & Khater (1992) public water supply systems can be assessed in three parts, being source, transmission system, and distribution system. The purposes of these are as follows:

1. Source

- the supply from which water is drawn eg. watershed, reservoir, river or ground water table. These may be some distance from the end user.

2. Transmission system

- transports water from the source to the service area
- comprises large pipelines (trunk lines), canals or aqueducts.

3. Distribution system

- an intricate network of small diameter pipes buried beneath city streets, delivering water in the service area, including to fire hydrants

Each distribution system may include various nodes such as pump stations, treatment plants and intermediate storage tanks, reservoirs, and possibly underground cisterns.

10.2.2

Lifelines (1991) listed the types of pressure pipes in service in the Wellington region and their usage, and this has been summarised in Table 10.1.

Table 10.1: Use of available pressure pipe materials in the Wellington Region

Trunk water mains	Distribution water mains	Service mains	Others
Spiral welded steel (coated and lined)	Spiral welded steel (coated and lined)	Galvanised (seamed) steel	Galvanised (seamed) steel for fire sprinkler mains
Ductile iron	Ductile iron	Polybutylene	Polybutylene for hot and cold water
µPVC	µPVC	µPVC	
Medium density polyethylene	Medium density polyethylene	Low density polyethylene (heavy wall)	
High density polyethylene	High density polyethylene	High density polyethylene	

The failure modes of buried pipe systems were also defined, as follows:

- the pipe itself may fail by excessive tension, compression, bending deformation, or shear
- the pipe may fail by buckling locally or as a long column
- excessive rotation at a pipe joint
- pull-out of a joint or failure of a spigot
- failure of the lining of a pipe while the outside of the pipe is still serviceable
- shearing off at a bend or junction or at a rigid structure
- excessive internal pressures and/or high hoop stress caused by over insertion of a pipe at a joint or spigot.

The effects of fault movement on buried pipelines subjected to large fault movements were also noted in Lifelines (1991). Pipelines undergo bending and axial deformation, either tension or compression depending upon the orientation of the pipeline to the fault.

It suggested measures for improving the performance of pipelines crossing a fault, as follows:

- use smaller pipe diameter
- take a larger crossing angle
- use a smaller buried depth
- use a pipe with a more ductile material
- ensure the pipeline is not fixed to rigid structures at either end of the fault ie. is not subject to restraint over the critical length.

10.2.3

Chung (1995) noted earthquake damage to water supply systems has been common in the past and can be expected in the future. NZSEE (1995) suggested that those experiences demonstrate the impracticability of stopping fire spread without water.

10.2.4

Public water supplies play a critical role in post-earthquake fire protection of the built environment. In order to fight aggressive growing fires, fire brigades depend in the first instance on water at the hydrants at pressure and in quantity. Provided that an adequate water supply is available the Fire Service is generally capable of containing major fires to limit spread, according to M&M (1991). However, it suggested that the relatively low level of seismic design incorporated into city water supplies in New Zealand, and the absence of practical emergency alternatives, would restrict the Fire Service's ability to limit fire spread.

10.3 Reported effects of earthquakes on public water supply systems and on fire-fighting tactics

10.3.1

Table 10.2 is a summary of the reported effects of earthquakes on public water supplies and on fire-fighting tactics, and suggests that:

1. Underground water distribution systems are very vulnerable to earthquake shaking and failures can be expected even in moderate earthquakes. In major earthquakes the damage caused below ground can be just as devastating as the structural damage at the surface, yet advances in the survival of underground water supply systems may not have matched the advances in the survival of structures. However, dams and reservoirs, in general, have good earthquake records.
2. The absence of water at hydrants can severely hamper fire-fighting operations and has been the reason why post-earthquake fires have been able to rage uncontrolled after some earthquakes and contribute to conflagration. The development of better means to ensure continued fire-fighting water supplies is critical.
3. There have been many instances after major earthquakes where fire-fighting efforts have depended on the availability of alternative water supplies to deal with fires in earthquake affected areas. Backyard swimming pools, street water storage cisterns, wells, moats, rivers, lakes and harbours have been used as sources of water when fire hydrants are unserviceable. However, the transfer of water to firegrounds by tandem pumping techniques can be extremely labour and equipment intensive unless the waterway systems are specially designed eg. San Francisco Fire Department's Portable Water Supply System (PWSS). Also, the viability of water-ferrying to fire locations by means of tanker trucks is largely dependent on the post-earthquake condition of the roading system ie. in terms of damage and congestion levels.

Table 10.2: Summary of reported effects of earthquakes on public water supply systems and on fire-fighting tactics.

Earthquake event	Reported effect of earthquake on public water supplies and on fire-fighting tactics
San Francisco, 1906	<p>Complete water supply failure due to:</p> <ul style="list-style-type: none"> • failure of three water transmission lines feeding the city where they crossed marshy ground • widespread damage to the distribution system in the city • service pipes were torn off by the burning and falling buildings and left running wide open. <p>This left little pressure in the mains pipes in the unburnt district and for the fire department along the burning margin between the two areas. Water supply failure seriously disrupted the fire department response and contributed to the conflagration.</p>
Japan, 1923	<p>Complete water supply failure occurred due to:</p> <ul style="list-style-type: none"> • network of underground water pipes traversing the city being demolished and broken in numerous places, and to massive leaks • water hydrants were destroyed by flames so that water leaked away. <p>Reservoirs of the city water works were damaged in the filter and cleaning beds, but water was not lost from the reservoirs.</p>
Japan, 1923 (continued)	<p>With the loss of the city water system fire-fighters attempted to get supplies from moats and other reservoirs at distant places. With these limited supplies they fought the fires for 46 hours continuously, and succeeded subduing outbreaks at 23 places, but 22 firemen were burnt to death and over 100 were injured. Water supply failure contributed to the spread of post-earthquake fire.</p>
Hawkes Bay, 1931	<p>Complete water supply failure occurred in Napier due to:</p> <ul style="list-style-type: none"> • fracturing of distribution pipes at junctions and lead packings at joints were disturbed, allowing extensive leakage • hill top reservoir was badly fractured and a high pressure water tower overturned. <p>Water pressure failed completely within an hour of the earthquake. Fire brigade did not have enough water to save many buildings, and attempted to keep the fire within bounds by pulling down and dynamiting buildings, to isolate blazing buildings</p>
Long Beach, 1937	<p>Underground main breakage occurred, particularly in filled ground on Long Beach waterfront. No details provided as to tactics of fire departments.</p>
Niigata, 1964	<p>Underground pipes including water lines were broken. No further details.</p>
San Fernando, 1971	<p>Damage occurred in all sections of the supply system, and included:</p> <ul style="list-style-type: none"> • cracked reservoirs • pumping stations inoperative (due either to structural damage or power supply failure to electric motor driven pumps) • distribution systems extensively fractured.
	<p>Acute shortage of water. Swimming pool water used for fire-fighting purposes where fire hydrants were unserviceable. Water tankers were used for the distribution of water during the period of shortage. Restoration of water within 4 - 5 days to less effected parts of the damage area, and to all areas within 4 weeks. Fire spread did not occur. Problems with public water supplies did not significantly impede the fire department's efforts.</p>
Managua, 1972	<p>Damage occurred to underground water distribution systems particularly in poor ground areas and across earthquake faulting. Absence of water at hydrants severely hampered fire-fighting operations, and was given as one of the reasons why fires were able to rage uncontrolled through many downtown blocks for over a week after the shock. At that stage firebreaks were begun to prevent there further spread. Pumps were set up to draw water from a lake. These actions, together with continued fire-fighting, were successful. This earthquake emphasised the sensitivity of cities to the survival of their water supplies.</p>

Table 10.2 (continued): Summary of reported effects of earthquakes on public water supply systems and on fire-fighting tactics

Earthquake event	Reported effect of earthquake on public water supplies and on fire-fighting tactics
Morgan Hill, 1984	Breaks in two transit water lines lead to large water losses. Numerous water service connection failures in high damage areas. The risk of an outbreak of fire in a residential area was of serious concern for several days following the earthquake due to water main breakages and supply failures. A water truck was stationed in the area with capacity sufficient to control a small fire.
Mexico City, 1985	<p>Complete loss of water supply in the central city area and to 4 suburbs, and severe curtailment in 6 other suburbs, due to serious damage to underground water system pipes. The earthquake caused damage below ground which was just as devastating as the structural damage at the surface. Types of water line damage were:</p> <ul style="list-style-type: none"> • shear failure, in the larger diameter pipes • telescopic failures, in the smaller diameter pipes. <p>Lack of water could have adversely affected fire-fighting ability. Pipeline repair took in excess of a year and during that time temporary water storage tanks were set up and replenished by tank trucks.</p>
Edgecumbe, 1987	Numerous breaks in water supply lines occurred which took over two weeks to repair. None of the references available reported the extent of the disruption to fire-fighting water supplies, nor the extent of demands placed on them.
Whittier Narrows, 1987	Water systems in the region performed well and there was little disruption to service from damage to transmission or distribution systems. Limited areas in Whittier were without fire-fighting water for periods of hours due to several dozen water main breaks and leaks. Peak pressure was only at 50% of normal during the two days following the earthquake. The disruption to water supply in the Whittier area did not cause any problems for the LA fire department.
Loma Prieta, 1989	<p>Water mains throughout San Francisco broke in areas of filled or infirm soil.. Marina District was severely impacted by 69 breaks in the high pressure water mains (Auxiliary Water Supply System or AWSS) affecting the supply to fire hydrants). Fire-fighting operations were severely affected in the Marina District and in the outlying residential district in the southwest of the city. The Portable Water Supply System (PWSS) was set up to deliver water to the fireground in the Marina District from a fireboat in the harbour. This enabled the fire to be confined to one square city block.</p> <p>This earthquake showed that underground water distribution systems are very vulnerable, and failure can be expected even in moderate earthquakes. It appears that advances in the survival of these systems has not matched the advances in the survival of structures, and the development of better means to ensure continued fire-fighting water supplies is critical.</p>
Hokkaido Nansei-oki, 1993	Fire-fighting water was drafted from four 40,000l underground cisterns distributed across the town. No reports available on the impact of the earthquake shaking on water supplies.
Northridge, 1994	<p>There was a lack of water pressure at hydrants during the hours and days following the earthquake in the western and northern parts of the San Fernando Valley arising from:</p> <ul style="list-style-type: none"> • breaks in at least 6 trunk lines • approximately 3,000 leaks in distribution lines • damage sustained to pumping stations and storage tanks. <p>In most other areas of the San Fernando Valley fire-fighting water supplies were generally adequate during the day of the earthquake, and Santa Monica's water supply system suffered no significant impairment.</p> <p>Post-earthquake fire-fighting effort depended on the availability of alternative water supplies to deal with fires in many of the earthquake affected areas (in common with the experiences from earlier major earthquakes).</p> <p>Alternative supplies used were backyard swimming pools and water tankers. Three days after the event water system pressures were re-adjusted by fire department pumpers.</p>

Table 10.2 (continued): Summary of reported effects of earthquakes on public water supply systems and on fire-fighting tactics

Earthquake event	Reported effect of earthquake on public water supplies and on fire-fighting tactics
Kobe, 1995	<p>Although 30,000m³ of water were conserved in city reservoirs protected by seismic shut-off valves, approximately 2,000 breaks occurred in underground piping, and most fire hydrants were dry due to the water losses. Alternative water supplies were used and these included swimming pools, a river, and the ocean. It required 6 pumpers in tandem to get the water to some firegrounds and proved to be extremely labour and equipment intensive. Water was also ferried by tankers to fire locations, but the debris-strewn and congestion-prone streets resulted in slow and difficult progress..</p> <p>Water for fire-fighting purposes was available for only 2 to 3 hours, but this proved difficult to get to the firegrounds.</p>

10.4 Possible effects of earthquake on the Greater Wellington, and Christchurch City and urban water supply lines

10.4.1

Wellington Engineering Lifelines Study

Lifelines (1991) considered two levels of earthquake in Greater Wellington:

1. The Moderate Wellington Regional Event.
2. The Wellington Fault Event.

Moderate Wellington Regional Event.

This was defined as the design level earthquake regional event, without local fault movement, of MM VIII intensity and likely to cause peak ground accelerations of 0.3g anywhere in the region. The assessed probability of such an event was about 50% in 50 years.

Under this level of earthquake shaking the water system is expected to perform quite adequately, although lead jointed and asbestos cement mains in soft or unconsolidated ground conditions are likely to experience some damage, but causing only localised disruption to supply. However, restoration of service to most areas is expected to be within hours.

Wellington Fault Event.

This was defined as the maximum credible event and related to a movement on the Wellington Fault causing an earthquake of MM X intensity, and local peak accelerations of 0.9g. The assessed probability of such an event was about 10% in the next 50 years. Under this level of earthquake shaking all four regional water supply lines are significantly at risk from the one major event. Each line is vulnerable at several points along its length due to soft sediments.

The predicted extents of damage are:

- at a district level -
 - a significant proportion (30 - 40 % is suggested) of distribution reservoirs and local networks will be disrupted
 - the prospect of reservoirs draining themselves through broken network pipes is very real.
- at a local level -
 - buried pipes in firm ground are likely to perform reasonably well
 - the incidence of damage to brittle pipe systems will be greater than for ductile pipes
 - in areas of soft soil or soil subject to liquefaction, damage to brittle pipes can be expected to be severe
 - pipes passing through embankments or at junctions or interfaces with structures, valve chambers or other soil type represent situations of increased vulnerability.

Lifelines (1991) predicted that recovery of a basic water service for priority use would take two days following the Wellington Fault Event. (Lifelines (1994) subsequently reported that a minimum of 5 days was a more realistic expectation, but that the stating of a specific time period is too simplistic, and could give rise to false expectations).

It was also noted that to achieve this minimum there is a high dependence on:

- communications (for damage assessment)
- power supply (for pumping stations)
- access and equipment.

It further predicted that to restore a 50% service would take two weeks, and a return to normal service could take 12 months.

10.4.2

Lifelines (1994) reported on the development of an integrated strategy for the Immediate Response phase following an earthquake, and how at a very early stage of the deliberations the following very fundamental question arose:

“Should the initial reaction of Territorial Authority water supply personnel be to shut down the system in order to conserve water supplies, or should the system be kept running in order to serve the requirements of the fire service?”

It noted that the relatively unknown nature of fire after earthquake in Wellington, coupled with the dramatic fires that followed the Northridge earthquake in January 1994, added to the uncertainty surrounding this question. Fire Service opinion was sought, and reported as:

- its first priority is to save lives
- it supported the installation of shut-off valves at reservoirs; it did not assume access to mains water, being prepared to use seawater where practicable and refill its tenders from designated supply points (eg. bores in the Hutt Valley, hydrants at reservoirs or off the Wellington Regional Council bulk mains)
- it was encouraging Territorial Authorities (TAs) to establish special hydrants with large diameter connections specifically for refilling Fire Service tenders.

It was reported that the Fire Service views gave a strong indication that it is expecting to have to “look after itself” after an earthquake in terms of water for fire-fighting, and that it supported the approach (of the TAs) for the systematic introduction of automatic shut-off valves at local key reservoirs.

10.4.3

Christchurch Engineering Lifelines Study

Lifelines (1997) described the earthquake adopted for the Christchurch Lifeline Study as a 150 year return period event of shaking intensities MM VIII - MM IX over most of the Christchurch area.

The Christchurch water supply system was reported as being rather vulnerable to that level of earthquake shaking, but due to a gridded configuration it has adequate diversity to get water to most places although the whole area would be subject to earthquake damage.

Some areas of flat ground would be subject to liquefaction and ground settlement, but pipelines would be exposed to the greatest seismic risk at bridge approaches where ground slumping could result in the shearing of pipes. In sloping areas on the hills landslides may also lead to pipe damage.

Lifelines (1997) reported that Christchurch has a total of 84 pumping stations, and 37 service reservoirs a number of which are of modern earthquake resistant design. Only 25% of the pumping stations have standby generators. These buildings have been structurally rated as follows:

- 40% of the pumping stations are at very low risk
- 40% are at low risk
- 20% are at high risk (being substantially constructed of unreinforced masonry).

Because the Christchurch underground reticulated water supply system is in general a massive grid network and is not dependent on long, isolated and unduplicated trunk mains, then after the shaking of the 150 year return period earthquake judicious operation of valves by Christchurch City Council Waterworks Department staff is expected to result in water getting to most places in the City and urban areas.

10.5 Sourcing and delivery of fire-fighting water from alternative supplies

10.5.1

Water supply is a critical factor in controlling fire damage and losses. As noted previously, it is inevitable that underground reticulated water supply systems will suffer damage in strong ground shaking. Water shortages arising through leakage from these systems should be countered by the ability of fire departments to source and deliver water to the firegrounds from alternative supplies.

The importance of on-site stored water supplies (and the associated diesel engine-driven pumps) to ensure the availability of water for building fire sprinkler systems in the event of loss of town main water supplies, has been noted in the previous chapter.

10.5.2

Scawthorn & Khater (1992) had noted that an above-ground back-up to reticulated systems can be crucial to combatting post-earthquake fire, as was evident in the San Francisco Marina District following the 1989 Loma Prieta earthquake.

The City of San Francisco had recognised this problem and established a Portable Water Supply System (PWSS). According to M&M (1991) this is credited with preventing the major fire in the Marina District worsening by one or two orders of magnitude.

Scawthorn and Khater described the PWSS as a unique above-ground water main system, supplied from hydrants off larger water mains, and capable of supplying an ample water supply to halt fire spread by means of water curtains and multiple master streams. It is a system of vehicles (hose tenders and pumpers), large diameter 5-inch hose, portable hydrants, and pressure-reducing valves, which permit deployment of an above-ground gridded water main system.

It was further described as follows:

- each PWSS hose tender carries a mile of large diameter hose, which can be laid out in 20 minutes to furnish large volumes of potable or fire-fighting water
- water can be drawn from any serviceable hydrant or, combined with specialised pumps capable of drafting water over a distance of 200 feet, any pond, bay, stream or other source
- portable hydrants interspersed along the hose permit fire-fighters to erect a mile long water curtain, while multiple hose tenders permit supply to almost unlimited lengths, or gridding of the above-ground system in a congested area.

10.6 Conclusions

10.6.1

This chapter discusses the role of public water supplies in the normal and post-earthquake fire environments, and how earthquake damage to these systems can affect fire-fighting tactics. The sourcing and delivery of fire-fighting water from alternative water supplies is also considered.

10.6.2

The main issues are:

1. Water is delivered to urban areas via large diameter transmission and distribution pipeline systems, which also include various nodes such as pumping stations, treatment plants and intermediate storage tanks etc. Water is generally supplied to fire hydrants from an extensive and intricate network of relatively small diameter pipes buried beneath city streets. Although fire trucks generally carry a limited supply of water, there may be a heavy dependence on fire hydrants for a continuous supply of fire-fighting water to fight aggressive growing fires.
2. Underground water distribution systems are very vulnerable to earthquake shaking and failures can be expected even in moderate earthquakes. Their reliability would be increased through structural improvements which include the replacement of cast iron and asbestos cement pipes in vulnerable areas with ductile pipe systems, the

strengthening of pipes and joints, and the introduction of flexible connections. Dams and reservoirs, in general, have good earthquake records.

3. Multiple simultaneous ignitions in urban areas following major earthquakes may greatly increase the demand for readily available supplies of water from fire hydrants over a wide area.
4. Providing adequate water supplies are available from fire hydrants or alternative supplies, fire brigades are generally capable of containing major fires to limit spread. However, experiences demonstrate the impracticability of stopping fire spread without water. With the absence of water at hydrants and where alternative water supplies have not been available, post-earthquake fires have been able to rage uncontrolled after some earthquakes and contribute to conflagration.
5. Swimming pools, street water storage cisterns, rivers, lakes and harbours have been used as sources of water when fire hydrants are unserviceable. The viability of water-ferrying to fire locations by means of tanker trucks is largely dependent on the post-earthquake condition of the roading system. Transfer of water to firegrounds by tandem pumping techniques can be extremely labour and equipment intensive unless the waterway systems are specially designed eg. San Francisco Fire Department's Portable Water Supply System.

CHAPTER 11.0

METHODOLOGIES FOR ESTIMATING FIRE LOSSES FOLLOWING EARTHQUAKES

11.1 Background

11.1.1

Although the risk posed by post-earthquake fires is significant and the losses from some past events have been enormous in terms of both life and property, it is generally acknowledged that over the years relatively little attention has been devoted to quantifying property losses from fire following earthquake.

11.1.2

This Chapter identifies the development over recent years of methodologies for analysing post-earthquake ignitions in the urban environment, fire spread, and resulting property losses. Their utility is discussed and compared, and their applicability to NZ conditions is assessed.

11.2 The problem

11.2.1

Post-earthquake fire spread is an important problem in urban areas of cities which have a large timber building stock. The hazard also exists in industrial facilities such as oil refineries, chemical plants etc.

Scawthorn (1986) noted that most cities in the United States, especially in the seismically active West eg. Cities of Los Angeles and San Francisco, have a fire spread potential due to the combustible nature and density of the built environment.

Japanese urban areas also typically have closely spaced dwellings of highly combustible construction and which by past post-earthquake fire events have demonstrated the potential for conflagration and very high losses.

Oppenheim (1984) acknowledged that in order to properly understand and estimate the magnitude of the post-earthquake fire spread problem a methodology for quantitatively determining the effects of post-earthquake fire spread was required. The overall problem had received considerable attention in Japan to that time, and in the United States Charles Scawthorn had been credited with distilling that research and presenting some powerful studies in seismic risk analysis incorporating fire loss.

Models have been developed that predict:

- number of post-earthquake ignitions as a function of earthquake intensity and location
- size of burn area, number of buildings lost due to fire spread, and value
- brigade response time to each fire
- amount of water required to suppress the fire at time of first engine's arrival
- number of engines and personnel required to apply this water

As many of the models are elaborate and too extensive to detail in this report only their main features will be discussed, and where possible their relevance is identified.

11.3 A review of the development of methodologies for estimating fire losses following earthquakes

11.3.1

Kawasumi Model, 1961

H.Kawasumi's modelling of fire outbreaks following earthquakes (circa 1961) was cited in EERI (1985) as the first study reported in Japan. The model used data from the 1923 Kanto earthquake to show a relationship between the rate of outbreaks of fire in wooden buildings and the rate of collapse of wooden buildings from earthquake shaking.

The utility of Kawasumi's model is limited, according to EERI (1985), as it was only based on 1923 data when the Japanese were using old-fashioned fire appliances, burning solid fuels such as wood and charcoal scarcely used nowadays.

11.3.2

Hamada Model, 1975

The work of H.Hamada in fire spread modelling was cited in Scawthorn et al (1981) and Oppenheim (1984). He was credited with developing (circa 1975) a semi-empirical model for a uniform grid of Japanese house construction, to investigate fire risk in urban Japan. It was an elaborate model but was used subsequently in many Japanese studies, and in the important work by Scawthorn (refer to Section 11.3.4 of this report).

Oppenheim noted its use of the independent variables:

- building spacing
- building height
- the mix (proportion) of one and two storey buildings
- wind velocity

It predicted a set of three fire front velocities which spread in an ellipse-like fashion. The burn area (or number of units burnt) therefore increases with time.

The model permitted a full picture of fire loss for that particular construction type, but due to the dependence on region-specific relationships, the specific relations determined were, according to Scawthorn, only applicable to Japan and regions with building structural and fire-resistive characteristics of urban Japan.

11.3.3

Mizuno Model, 1978

H.Mizuno's work in determining post-earthquake fire incidence was cited in EERI (1985) and in Scawthorn (1986). He examined (circa 1978) Japanese data from the Kanto and Tango earthquakes to determine a correlation between building collapses and ignitions, using building damage as a measure of seismic intensity.

EERI (1985) noted that the regression analysis over-estimated the rate of fire outbreaks, and a biased selection of data was used, bringing into question the utility of Mizuno's model in the estimation of fires from future earthquakes.

11.3.4

Scawthorn Model, 1981

Scawthorn et al (1981) reported the work of C.Scawthorn, Y.Yamada and H.Iemura. They formulated a model for the determination of post-earthquake fire spread among low-rise wooden buildings in urban regions. The model considered:

- building density and properties
- wind velocity
- fire-fighting response and deterioration of response with increasing seismic intensity.

The model was claimed to:

- be applicable to specific earthquakes and allow the probability of annual expected losses due to fire spreading to be determined
- be in satisfactory agreement with the observed fire spreading in the 1923 Tokyo, 1948 Fukui and 1978 Miyagiken-oki earthquakes
- indicate annual expected fire spreading losses to be about 50% of structural shaking losses when applied to the Osaka region of Japan (that fire losses can exceed shaking losses under certain circumstances was acknowledged).

The authors also acknowledged that although the methodology was general, it relied somewhat heavily on empirical relationships that are region-specific, depending on structural and fire-resistive characteristics of the buildings comprising the urban regions of Japan. Application of the methodology to the western United States or other regions with significant post-earthquake fire risk would have necessitated the determination of empirical relationships appropriate to the areas under investigation.

A summary of the methodology is as follows:

1. Postulated the occurrence of an earthquake
 - either probabilistically, on the basis of seismic hazard analysis (Scawthorn used a semi-empirical relationship based on data from Sendai City in the 1978 Miyagiken-oki earthquake), or
 - specifically.
2. Estimated the outbreak of serious fires using Mizuno's regression analysis relating the outbreak of serious fires to the ratio of collapsed low-rise buildings.
3. Estimated the number of low-rise buildings destroyed by fire spread using Hamada's model of fire spreading for urban Japan, but modified as explained below.
4. Estimated the expectation of loss of buildings due to fire spread, in terms of loss per building (with total buildings being the total of collapsed buildings).

In Stage 3. of the methodology, the problem of determining how long fires will continue to spread under post-earthquake conditions was addressed by the authors.

Two assumptions were made, and mathematically approximated:

- a) post-earthquake response times of fire-fighting teams deteriorates with increasing severity of ground shaking, due to rubble, traffic jams, confusion, damaged water supplies etc.
- b) after the fire-fighting team responds the time required to suppress (ie. halt or contain) the spread of fire must reflect, for larger fires, economies of scale in the provision of fire-fighting resources, perimeter only fire-fighting, concentration of resources etc.

The authors recommended further investigation of deteriorating fire-fighting capability as noted in a) above. This was later addressed by Scawthorn in the development of his 1986 model.

11.3.5

Oppenheim Model, 1984

The development of an ignition frequency estimation for the United States West Coast was reported in Oppenheim (1984).

In that study, and in keeping with the convention of the day, the ignition frequency is compared with the damage frequency of the building stock (the damage frequency is taken as the surrogate for earthquake intensity). Using field data generated in Japanese experiences, and some sparse data from several United States earthquakes, L. Oppenheim developed a relationship to describe the initial ignition frequency and the direct damage frequency as follows:

$$\log \phi = -3.13 + 0.54 \log \theta$$

where ϕ denotes the initial ignition frequency
and θ denotes the direct damage frequency.

Under conditions of full destruction (ie. $\theta = 1$) the ignition frequency is $\phi = 0.00074$ (ie. 7.4 ignitions in 10,000 damaged buildings)

In an earthquake which destroys 10% of the buildings in a neighbourhood (ie. $\theta = 0.1$) the ignition frequency is only $\phi = 0.00021$. (ie. 2 in 10,000 damaged buildings)

Oppenheim considered the result to represent at that time the best estimate for ignition frequency in United States residential construction.

11.3.6

Scawthorn Model, 1986

Scawthorn (1986) reported the further development of a simulation model for post-earthquake fire in the United States . The diversity, significance and complexities of fires following earthquakes had been further reinforced by the 1983 Coalinga and 1984 Morgan Hill events, and particularly in the area of fire-fighting capability. The author used data from these and previous United States events to generate a correlation between:

- number of fires (normalised by building floor area and expressed as single family equivalent dwellings of 1500 sq.ft. floor area), and
- earthquake intensity (on Modified Mercalli scale).

“Number of fires” were defined as those ignitions which had developed into major structural fires, requiring trained fire service personnel and equipment for suppression.

The correlation permitted Scawthorn to deduce a fire initiation rate, and this has been repeated in Table 11.1. A conversion of this data presented in Cousins et al (1990) is also reproduced.

Table 11.1: Fire Initiation Rate
Data Sources: Scawthorn (1986) and Cousins et al (1990)

Earthquake intensity (MMI)	Fire initiation rate (One fire per stated number of SFED: see Note) Scawthorn (1986)	Fire initiation rate (per million sq. m floor area) Cousins et al (1990)
VI	Negligible	0
VII	7,500 SFED	1
VIII	3,500 SFED	2
IX	2,500 SFED	3

Note:

SFED denotes “Single Family Equivalent Dwellings” with basic floor area of 1,500 sq. ft. (140 sq.m)

Fires ignited at the ignition rates described in Table 11.1 above will spread, first within one structure and then to adjoining exposed structures. Scawthorn noted that the spread was based on a regular arrangement of buildings, with spread most rapidly downwind, but also occurring side- and up-wind.

As a further part of the development of the 1986 simulation model Scawthorn quantified fire spread using the model previously established by Hamada, but modified for application to typical urban United States building stock. Typical results (Source : Scawthorn, 1986) using these relations and after 20 minutes of burning of an unfought fire, have been redrawn for this report and illustrated in Fig. 11.1. It suggests that the number of buildings burnt in any given time period will be in rough proportion to wind speed.

However Cousin et al (1990) has noted that data from major urban fires in the United States suggests a different relationship between rate of fire spread (or total buildings burnt) and wind speed.

Data reproduced by Cousins et al and attributed to work by C. Scawthorn in 1987 indicates the following pattern:

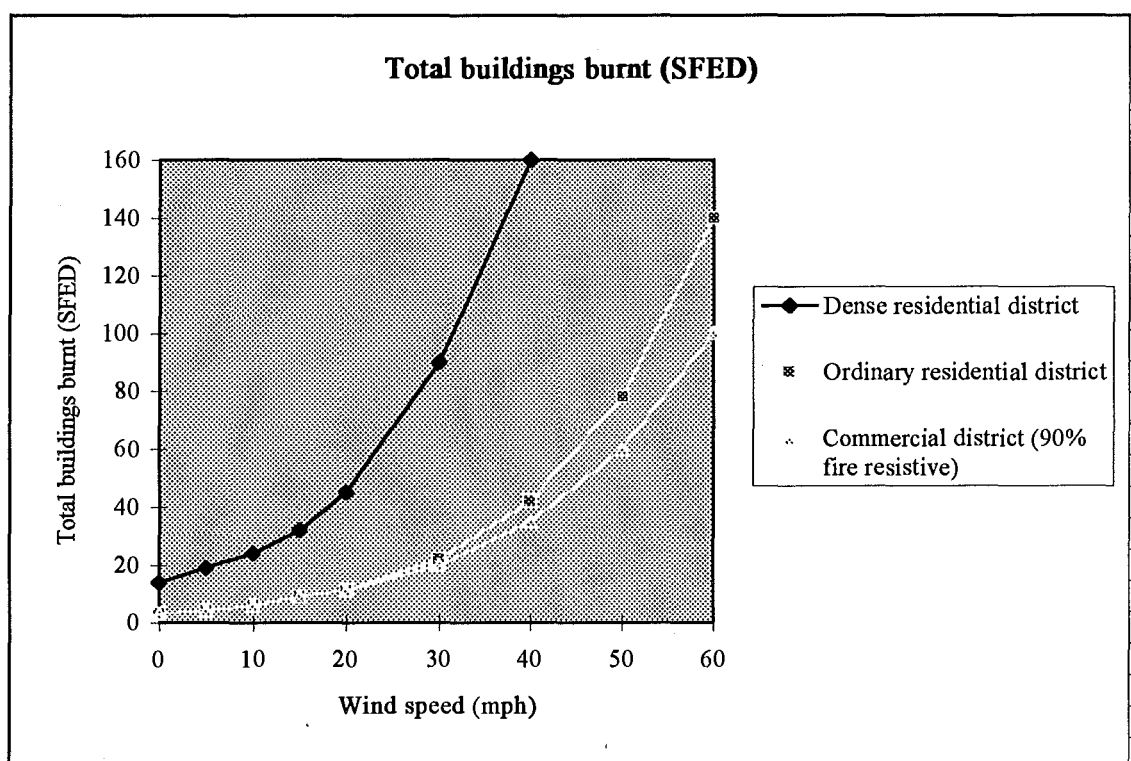
- a slightly increasing rate of fire spread with increasing wind speed, from still air conditions up to about 10 km/hour
- a decreasing rate of fire spread with increasing wind speed, for speeds up to about 40 km/hour
- an increasing rate of fire spread thereafter.

Scawthorn noted that his 1986 model allowed for details of fire service operations in the post-earthquake environment. As identified in Chapter 6 of this report, multiple simultaneous ignitions are the essence of the post-earthquake fire problems in that fires that would be easily extinguished under normal conditions grow into large fires (and under certain conditions, into conflagrations) because they are not responded to, due to insufficient fire service resources for the number of fires ignited at the same time in the aftermath of the earthquake.

The major elements of the problem of fire service response to multiple simultaneous ignitions were factored into a “Fire Department Operations Timeline” depicted in Scawthorn (1986), and for which a computer programme was developed to analyse and apply the process. This programme was reported to contain algorithms to perform the following:

- determine the number of ignitions, assign a number to each fire, and track fire growth
- determine fire reporting time and fire engine arrival
- track each fire engine from location to location
- calculate final burnt area for each ignition as a function of, fire growth and applied fire suppression capacity.

Fig. 11.1: Total buildings burnt after 20 minutes from downward wind spread.
Data Source: Scawthorn (1986)



Notes: Total buildings burnt at increasing wind speeds and for unfought fire spreading. For typical urban United States building stock as identified, and stated in terms of Single Family Equivalent Dwellings.

The considerations Scawthorn took into account in computer modelling fire service operations in the post-earthquake environment are summarised in the following:

1. Initial period of delay by citizens in response to, and in the reporting of, fire ignitions due to confusion and concern for personal safety.
2. Further significant delayed responses (during which small fires grow out of control), and resulting from disruption to
 - communications to fire departments of reports of fires (due to impairment of the telephone service through damage or overload) and which will then likely be made, following the initial period of confusion, by citizens travelling to the nearest fire station
 - communications within the fire service (eg. fire dispatch etc.)
3. Delay in arrival of fire department apparatus in response to a fire report
 - because street access may be impaired or blocked by collapsed structures or traffic congestion
 - because of “clumping” of ignitions, and responding fire engines will be travelling from distant districts
4. Time for fire attack and suppression, which will vary depending on the tactics adopted. These would include normal procedures, and minimal tactics which may constitute:
 - “flood and run” (ie. deluge deliveries followed by dispatch to the next fire as soon as possible, but note that any rapid suppression tactic is not intended to minimise property damage)
 - or abandonment of the burning structure and protection only of exposures
 - or recognition that exposed structures cannot be protected, with fall back to a defensible line eg. abandonment of a city block with attempt to stop the fire at a wide street
 - or total abandonment ie. recognition that either little or nothing can be done, that the fire will burn itself out at an identified firebreak with or without fire department intervention, or that the apparatus is required at more critical situations).
5. Impairment of water supplies due to damage to underground piping in poor soil areas (discussed in Chapter 10).

Scawthorn noted the application of his 1986 analytical model to the City of San Francisco, because of its long established seismic risk from the San Andreas and Hayward faults, each located approximately 8 miles from the CBD and capable of predicted M 8.3 and M 7.5 events respectively. The factors seismic intensity, ignition rate, fire spread and fire service operations were incorporated in his computer model.

For a range of earthquake intensities and wind speeds the computer model generated data which, as indicated by a limited set of results published in Scawthorn (1986), included the following:

- number of outbreaks of fire
- brigade response time to each fire (mins)
- amount of water (Mgpm) required to suppress the fire at time of first engine’s arrival
- number of engines required to apply this water

- number of personnel required
- size of burn area (acres)
- number of burnt buildings
- property losses (\$mil)

Table 11.2 reproduces for use in this report a summary by Scawthorn of first arrival requirements for the predicted, and other shaking intensities, and a wind speed of 10 mph.

Table 11.2: Summary first arrival requirements, San Francisco as published in Scawthorn (1986). Wind: 10 mph

Scenario earthquake Richter magnitude	No. of fires	Engines required at first arrival	Total No. of burnt buildings (SFED)
5.3	1	12	3
6.0	4	24	144
6.5	12	108	(see Note)
7.0	23	211	"
7.5	32	276	"
8.3	40	529	"

Note: Fires uncontrollable, allowing for deployment of reserve engines and limited mutual aid.

Scawthorn acknowledged that modelling shows fire following earthquake is a significant problem that, in the case of San Francisco, will dominate shaking damage in the future, as it did in 1906.

11.3.7

Cousins, Dowrick & Sritharan Model, 1990

The work of W.J.Cousins, D.J.Dowrick and S.Sritharan (then of the DSIR Physical Sciences, Lower Hutt) is reported in Cousins et al (1990). This assessed the urban property loss due to post-earthquake fire resulting from the Wellington fault event, as defined in Chapter 10 of this report.

As an alternative to the use of Scawthorn's 1987 rate of fire spread model the present authors developed a post-earthquake fire scenario to realistically estimate by "on-the-ground" inspection the spread of fire from a specified set of ignition sites, and chosen so as to be average and predictable as possible.

They noted the rejection of the use of Scawthorn's model for the following reasons:

- insufficient time to collect the necessary input data on buildings in the Wellington region: ie sizes, spacings, types of construction and fire resistance
- the contention that previous use of the model in the United States had given only rather general agreement between calculated and estimated rates of fire spread within an 8:1 range or variability, due to inherent statistical uncertainties.

The assumptions made in the scenario and noted by Cousins et al were as follows:

1. Earthquake was the Wellington fault event, although two other earthquakes were included in the study (ie. the Subduction zone and the Wairarapa fault) but not described in their report.
2. Number of earthquake-caused ignitions were assessed according to the Scawthorn 1986 model relating initiation rate and earthquake intensity.
3. Location of the ignitions were distributed semi-randomly over each location in the Wellington region, with care being taken to include a complete range of building types and housing densities, and to avoid unrealistic sites and topographies.
4. Average climatic conditions for the region could be taken and wind would not play a significant role in urban fire spread; the authors claimed that contrary to popular mythology wind speeds throughout the Wellington region (1990) are usually not high and only rarely exceed 40 km/hour (assumption for the purposes of the scenario was that wind speed would not play a significant role in urban fire spread in Wellington and this was predicted to be true for 90% of the time); refer to earlier comment citing Cousins et al in Section 11.3.6 of this report.
5. Fires would burn to natural boundaries with the Fire Service basically enforcing the boundaries whenever manpower and equipment were available. This was further qualified by the following -
 - For the Wellington City area it was predicted that resources would be entirely inadequate to deal with the expected high level of ignitions (about 38) and the high level of non-fire related demand.
 - For localities outside of Wellington City where it was predicted that the Fire Service had sufficient resources in relation to the number of post-earthquake ignitions (about 47) fire brigades would be able to operate in an extreme multiple-incident mode, mains water supplies would not be disrupted due to lower shaking intensities in the outer regions, and fires would be prevented from spreading beyond the structure of origin.

Each fire site was visited by the assessment team, natural boundaries to fire spread were located for each case and the area of destroyed property was estimated. Results were expressed in terms of number of houses destroyed for domestic property, and in square metres of floor area for commercial property. The basis for this was as follows:

- for domestic property it was assumed that one house would be destroyed per ignition with each "house" having a floor area of 140 sq.m.
- for commercial property one structure would be destroyed per ignition, taking 4,300 sq.m as an average of all commercial structures

Replacement values of the destroyed property were then estimated using regional valuation data, and after appropriate statistical analysis (as described by the authors) summed to give the total losses (refer to Chapter 13 of this report for values).

Cousin et al noted an interesting aspect of the result: ie. the dominance of the commercial losses, which made up about 80% of the total fire losses, despite commercial property value amounting to about 25% of total exposure.

They gave two main reasons:

1. Commercial buildings are very much larger than houses.
2. There is a greater potential for fire spread amongst the older commercial buildings of Wellington.

The limitations of the study were acknowledged as follows:

1. The impossibility of forecasting with precision the occurrence of a future earthquake event.
2. Dependence on imperfect knowledge of past events and of future conditions.
3. Reliance on the apparent robustness of taking averages of the effects on large numbers of properties.

However, the authors acknowledged that the various limitations on the data and analytical models, well recognised by the risk assessment industry, had been addressed in their study, as reported, of fire loss in the Wellington region.

11.3.8

Scawthorn and Khater Model, 1992

The All-Industry Research Advisory Council (USA) (since renamed the Insurance Research Council) was cited by Scawthorn and Khater (1992) to have developed the study "Fire Following Earthquake: Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco", in 1987. This established estimates of the potential losses that would occur due to fires following a large earthquake in these selected metropolitan areas.

That study was expanded in 1992 by C.Scawthorn and M.Khater using additional seismic events and an enlarged geographical area (which included the Seattle and Memphis metropolitan areas). Each of the earthquake scenarios used were claimed to have historic precedent and are the most damaging that could credibly be thought to impact these areas and result in large fires. The study predicted these to be widespread conflagrations causing fire damage in the billions of dollars, and having more severe impacts than previous events because of a much larger population and building inventory.

A further reason for the expectation for the greater severity of these events, as given in Scawthorn and Khater (1994), was that urban built environments contain vastly greater quantities of fuel, hazardous materials, and ignition sources than ever before.

The methodology employed to estimate losses in the Scawthorn and Khater (1992) study, and further clarified in Scawthorn and Khater (1994), is summarised in the following:

1. An estimation of shaking intensity (MMI) and the resulting shaking damage to the buildings and other structures in the region was made
 - shaking damage was estimated as a function of intensity and construction type, and was of interest only to assess the deterioration in fire protection features of buildings (eg. loss of facade increases the exposure)
 - damage to the water supply system and its remaining functionality was also estimated, based on shaking intensity and likelihood of liquefaction (further details follow; also refer to Glossary to this report for a definition and explanation of the effects of liquefaction).
2. Outbreaks of fires caused by the earthquake were then estimated, as a function of building density and shaking intensity (only serious fires which require the response of the fire brigade, were considered). Growth of each of these fires is tracked during two distinct phases
 - the initial period during which the fire is reported, and the fire department travels to the fire, and
 - the suppression period, during which fire-fighters attempt, successfully or otherwise, to extinguish the fire (unsuccessful suppression of the fire may result from inadequate apparatus, or insufficient manpower or water supplies).

A summary of the estimated number of fires caused by the earthquake, and prepared from data published in Scawthorn and Khater (1994), is provided in Table 11.3. of this report.

3. Fire losses are then estimated in terms of their mean and probabilistic distribution by using numerical simulation techniques to incorporate building density, materials and their post-earthquake condition, wind speed, average firebreak width, water supply functionality, and fire service response including mutual aid.

Further clarification of how post-earthquake water supply functionality, fire growth and fire department operations, and fire hazard at the wildland-urban interface were addressed in the above methodology, are summarised in the following paragraphs.

Water supply systems were considered in three parts: source, transmission, and distribution systems (defined in Chapter 10 of this report. A model methodology (cited in Scawthorn and Khater (1992) as ATC 25-1 and developed by FEMA) was adapted to estimate remaining water supply functionality and reduction in fire suppression capability of the water systems in northern and southern California, in relation to four of the earthquake scenarios used for the 1992 model. The present authors acknowledged use of the findings of earlier researchers for the Memphis and Seattle Water Systems.

Stages 2. and 3. as noted above were assessed by means of the analytical model of the Fire Department Operations Timeline developed by Scawthorn for the 1986 model, and referred to in Section 11.3.6 of this report

Table 11.3: Estimated number of fires caused by large earthquakes in selected areas of USA, as estimated in Scawthorn and Khater's (1992) study

Scenario earthquake and Richter magnitude	Location affected	Mean number of fires requiring Fire Department (FD) response	Mean number of large fires (see Note 1.)	Large fires as % of all fires requiring FD response
On northern San Andreas fault M 7.8 or on Hayward fault M 7.1	San Francisco Bay area	247	132	53
		209	103	49
On Newport - Inglewood fault M 6.8 or on southern San Andreas fault M 7.7	Los Angeles basin	516	365	70
		200	108	54
Puget Sound area M 7.5	Seattle	94	84	90
On southern segment of New Madrid fault M 7.6	Memphis area	232	217	94

Note:

Large fires are those out of control at first arrival (ie. fires that cannot be suppressed by one fire engine)

The analysis also considered the presence of brush zones at the wildland-urban interface which provide a highly flammable pathway from structure to structure and rapid fire spread potential. Scawthorn and Khater noted that with the growth of urban areas into more rugged terrain on the margins of the Los Angeles and San Francisco regions the area is exposed to large potential property losses, in the event of very rapid fire spread created by circumstances of high vegetation flammability during the dry season and high winds.

To factor-in the hazard of brush zones, the 1992 analysis considered fire losses for two cases, and the resulting regional fire losses are a summation of these fires:

- a) ordinary, non-high hazard conditions, occurring about 90% of the time (resulting in a number of medium to large fires that are typically contained within the city block of incidence), and
- b) dry, hot high wind conditions, occurring about 10% of the time (resulting in a few or more fires that cannot be extinguished and grow out of control, crossing city streets from block to block, and evolving into conflagrations).

Scawthorn and Khater noted that, typically, conflagrations are found to burn for several or more blocks until encountering a large firebreak (eg. a freeway, athletic field, park etc.) where they are either stopped by the available fire-fighting resources or in some cases, simply burn themselves out.

A summary of the mean losses from fire damage to property as estimated using the 1992 model and published in Scawthorn (1992) have been reproduced in Table 11.4 of this report.

Scawthorn (1992) noted that the validity of the 1992 model had been checked for comparison against experience data from three recent events:

- 1987 Whittier Narrows earthquake
- 1989 Loma Prieta earthquake, and
- 1991 Oakland Hills fire.

Numerous fires occurred in the aftermath of the two earthquakes, but the total number of fires was significantly less than the number of fire engines available, and conflagration was prevented. In the Oakland Hills fire the wind speed caused very rapid fire growth which could not be matched by the real-time response of the fire departments involved, and conflagration resulted.

Table 11.5 of this report reproduces the data from the model validation tests published in Scawthorn (1992). The methodology was acknowledged to produce reasonable estimates of fire losses.

Table 11.4: Predicted mean losses from fire damage to property following large earthquakes in selected areas of USA, as estimated in Scawthorn and Khater's (1992) study.

Scenario earthquake and Richter magnitude	Location affected	Estimated 30-year probability	Estimated mean loss due to fire damage to property (see Note 1) (\$US billion)	Estimated value of total property at risk (\$US billion)	Estimated mean loss as % of value of total property at risk
On northern San Andreas fault, M 7.8 or on Hayward fault, M 7.1	San Francisco Bay area.	67% for M7 or greater	7.3	655	1.1
	City of San Francisco		5.9	98	6.0 (see Note 2: 6x)
	San Francisco Bay area		4.0	655	0.6
	City of San Francisco		2.4	98	2.5 (see Note 2: 4x)
On Newport - Inglewood fault, M 6.8 or on southern San Andreas fault, M 7.7	Los Angeles Basin	Moderate	6.5	1,500	0.4
		High	2.7	1,500	0.18
Puget Sound area, M 7.5	Seattle	Not given	4.5	85	5.0 (see Note 3)
On southern segment of New Madrid fault, M 7.6	Memphis area	Not given	2.6	58	4.5 (see Note 3)

Notes:

1. In addition to the cost of damage caused by building collapse and other direct effects of seismic shaking and ground movement.
2. City of San Francisco post-earthquake fire risk is about four to six times higher than the Bay area as a whole.
3. Study areas are inner urbanised areas, so that the % of loss is relatively higher than for California events which (except for City of San Francisco) consider entire metropolitan areas.

Table 11.5: Model validation data.
Reproduced from Scawthorn and Khater's (1992) study.

Event	Model	Observed
1987 Whittier Earthquake:		
Ignitions	29	38
Property losses	\$B1.5	\$B2.4
1989 Loma Prieta Earthquake:		
All sites -		
Ignitions	65	53
Property losses	\$B45	?
San Francisco Marina District -		
Ignitions	1	1
Property losses	\$B14	\$B7.4
1991 Oakland Hills Fire:		
Losses (SEFD)	3,498	3,810

11.3.9

Hopkin's Earthquake Damage Assessment, 1995

Hopkins (1995) reported an assessment of the repair cost for buildings and infrastructure damaged in the Wellington fault event (defined in Chapter 10 of this report). The study also identified the cost of consequential fire losses, whose assessment was based on a value of 1% of replacement value for buildings and contents, as suggested in the report M&M (1991).

This method of assessment contrasts with the use of analytical methodologies based on post-earthquake fire initiation and fire spread models as reviewed in the previous sections of this report.

Hopkins noted that the data used in his study was based on damage assessments provided by public and private organisations, and acknowledged this permitted a broad assessment of earthquake damage to the total built environment, which included the Engineering Lifeline services.

In his study a single damage ratio had been assigned to each main class of asset. The general form of damage ratio, D_r , used was as defined by the relationship given in Lifelines (1993) as follows:

$$D_r = \frac{\Sigma \text{ Cost of material damage}}{\Sigma \text{ Value of property at risk}}$$

where the value of property at risk was taken as the replacement value.

Hopkins cited the United States Federal Emergency Management Agency publication ATC-13 as his source of damage ratios, this document being acknowledged in Lifelines

(1993) as the most wide-ranging compilation of information relating to damage ratios relevant to New Zealand conditions.

The values chosen were claimed to have represented a reasonable estimate of likely damage, but Hopkins cautioned for the need to interpret them in the light of the wide margin of uncertainty which exists in the derivation of damage ratios.

A summary of the dollar values as reported in Hopkins (1995) for the earthquake and consequential fire damage from a Wellington fault event, are included in Chapter 13 of this report for the purpose of comparison with those obtained by Cousins et al, using their fire scenario model and “on-the-ground” inspection technique for assessing urban property loss.

11.3.10

Operational application of computer models

In 1992 the Tokyo Metropolitan Fire Department introduced to operational service a computer based model which simulated potential outbreaks of fire following a major earthquake. According to FIRE INTERNATIONAL (1992) versions of the programme working on personal computers were put into service at all 77 of Tokyo’s fire stations to provide an inter-active data base for the retrieval of information on each fire station’s area of responsibility, including types of building construction, location of hazardous areas and of water supply access points. In addition the system could model the probable extent, direction and speed of a major conflagration for given wind direction and velocity data inputs, and output data which could be used for planning fire-fighting operations and devising evacuation plans.

11.4 Area of need for further post-earthquake fire modelling

11.4.1

Although most, but undoubtedly not all, post-earthquake fire ignition sources and scenarios have been identified, Chung (1995) considered that they have not been adequately confirmed and quantified following past earthquakes.

It was recommended that a model should be developed to:

- assess ignitions and fire scenarios, and
- assess the impact of actions needed to reduce ignitions, and to contain or suppress post-earthquake fires.

11.5 Applicability of post earthquake fire loss models to NZ conditions

11.5.1

Need for post-earthquake fire loss modelling in New Zealand

New Zealand is at significant risk from earthquake. The maximum credible Wellington fault event (refer to Section 10.4 of this report) has an assessed probability of about 10% in the next 50 years (with a predicted MM X intensity, and local peak accelerations of 0.9 g in the City of Wellington and urban areas).

The relatively unknown nature of fire after earthquake in Wellington City was acknowledged in Lifelines (1994). However, from the evidence noted in this report of recent post-earthquake fires in cities and urban areas of Western United States and Japan (refer to Appendix 2), it is reasonable to anticipate major property losses from fire following a severe regional or local fault event in any major urban area of New Zealand. A likely reason would be the fire growth and spread from post-earthquake ignitions, and contributing factors could include fire brigade resource overload, disruption to road access for fire appliances, and impairment of fire-fighting water supplies.

There are significant differences, however, between city and urban environments in New Zealand and the earthquake prone areas of United States and Japan which lessen the parallels, and considerably reduce the likelihood of post-earthquake fires growing to conflagration proportions in New Zealand areas. These differences (which in terms of property losses, would have mitigating benefits to the New Zealand built environment) would include:

- superior structural and material fire resistive characteristics of building stock
- greater separation distances between building stock, and wider streets (through more enlightened Town Planning and strictly enforced controls)
- lesser hazard from flammable vegetation within and at the extremities of the built urban environment ie. at country/urban interfaces (as compared with the high vegetation flammability at Californian wild/urban interface brush zones, through seasonal high winds and high temperatures).

Given the significant possibility of major property losses from post-earthquake fire in New Zealand we must assess the risk accurately, and if catastrophe is to be avoided set in train the steps necessary to mitigate the risk.

11.5.2

Application of overseas fire loss models in New Zealand

It is most likely that recently developed post-earthquake fire loss models eg Scawthorn and Khater's 1992 model would need significant adjustment for use under New Zealand conditions, and may depend on experience data for New Zealand which is not in fact available due (fortunately) to the low incidence of fires following past earthquakes.

Although a detailed judgement of the adjustments needed to the 1992 analytical model in order to apply it to New Zealand conditions suffers from the writer's lack of detailed knowledge of the model, it could be expected that the following factors at least would need to be considered:

- empirical relationships appropriate to New Zealand urban regions (eg. number of fires in relation to earthquake intensities)
- water supply functionality, and reduction in suppression capability
- fire service operations (to account for appliance capabilities and fire-fighting tactics)

Adequate preparation for, and response to fire following earthquake is extremely difficult but is aided by the type of computer based analytical modelling techniques as reviewed in this chapter. Application of fire loss modelling to New Zealand conditions may indicate whether in the future fire damage following a major earthquake event in New Zealand will dominate shaking damage, as has been evident in some past catastrophes overseas.

11.6 Conclusions

11.6.1

This chapter discusses the development of methodologies for analysing post-earthquake fire ignitions and fire spread in the urban environment, and the resulting property losses. Their utility is compared, and their applicability to New Zealand conditions is assessed.

11.6.2

The main issues are:

1. Methodologies have been developed for quantitatively determining the effects of post-earthquake fire initiation and spread. Work up to the early 1980's was done mainly in Japan by those including H.Kawasumi, H.Hamada, H.Mizuno, and Y.Yamada and H.Iemura in association with Charles Scawthorn. All relied on empirical relationships specific to buildings comprising the urban regions of Japan and used data from previous Japanese earthquakes. The research areas covered:
 - Rate of fire initiation in relation to rate of collapse of wooden buildings (Kawasumi in 1961, and Mizuno in 1978)
 - Fire spread in wooden buildings (Hamada in 1975)
 - Fire spread, and also considered fire-fighting response and the deterioration of response with increasing seismic activity, to assess fire spread losses (Scawthorn, Yamada and Iemura in 1981)
2. Application of the methodologies separately by Oppenheim and Scawthorn to the Western United States occurred in the mid-eighties, and required the determination of empirical relationships appropriate to those regions. The research areas covered:
 - Initial ignition frequency and direct damage frequency (as the surrogate for earthquake intensity) using a mix of Japanese field data and sparse data from several US earthquakes (Oppenheim in 1984).
 - Initiation rate related to earthquake intensity, and fire spread using Hamada's work modified for application to US building stock. Also allowed for details of fire service operations in the post-earthquake environment using a computer programme to analyse and apply fire service response (Scawthorn in 1986).
3. In 1990, W.Cousins, D.Dowrick and S.Sritharan assessed urban property loss due to post-earthquake fire resulting from the predicted Wellington, New Zealand, fault event. They applied some of Scawthorn's 1986 work relating to fire initiation rate and earthquake intensity, but developed their own method using "on-the-ground" inspections for estimating the spread of fire from a specified set of ignition sites. Natural boundaries to fire spread were established at each fire site and the area of destroyed property estimated. After appropriate statistical analysis using the replacement values of the destroyed property, total losses were assessed to be in a 95% probability range of \$60 M - \$620 M.
4. Scawthorn and Khater established estimates of the potential losses that would occur due to fires following large earthquakes in Greater Los Angeles and San Francisco, and in the Seattle and Memphis metropolitan areas.

The methodology for this extensive work in 1992, expanding on an earlier study in 1987, included the following estimations:

- Shaking intensity and resulting shaking damage to buildings in the regions.
- Fire initiation and growth.
- Fire losses, and taking into account building density, materials and damage levels, wind speed, average firebreak width, water supply functionality, and fire service response using Scawthorn's analytical model developed in 1986.

The study predicted widespread conflagrations causing fire damage in the billions of dollars, and having more severe impacts than previous events because of a much larger population and building inventory. Model validation tests acknowledged the fire loss estimates to be reasonable.

5. D.Hopkins also identified the cost of consequential fire losses following the Wellington fault event. His 1995 study was based on damage assessments provided by private and public organisations of the total built environment and fire losses estimated at 1% of replacement value for buildings and contents. His assessment of Regional consequential fire losses was \$56.7 M, being almost at the lower end of the 95% probability range as calculated by Cousins et al using an analytical methodology based on post-earthquake fire initiation and an "on-the-ground" inspection technique for assessing urban property loss.
6. Understanding and estimating the magnitude of post-earthquake fire losses requires the use of analytical methods which are based on models of earthquake damage levels, ignition and fire spread, fire brigade response, water supply functionality, and undoubtedly other factors which have not been identified. Empirical data used for establishing these models must relate to the urban area, region and country under investigation. These requirements therefore limit the general utility of models already established for specific urban environments in Western United States, and in Japan. Their application as fire loss models to New Zealand or other regions with significant post-earthquake fire risk therefore need to reflect the specific local conditions and experience data, but this may well be challenged by the lack of quantified and confirmed data in respect of major issues, such as fire ignition sources and fire initiations, water supply functionality etc. in relation to past earthquakes.
7. A benefit to New Zealand from the application of fire loss modelling to the conditions in this country will be the quantification of the potential for future fire damage in earthquake-prone urban areas, and an indication of whether fire damage will dominate shaking damage, as has been evident in some past catastrophes overseas. This is critical information for the adequate preparation and response to fire following earthquake.

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CHAPTER 12.0

CODE REQUIREMENTS FOR THE SERVICEABILITY OF ACTIVE FIRE PROTECTION FOLLOWING EARTHQUAKES

12.1 Background

12.1.1

When a building survives a major earthquake it is reasonable to expect the fire safety systems within it will also survive and remain capable of protecting life and property.

12.1.2

This chapter reviews code requirements for the serviceability of automatic fire sprinkler systems and fire alarm systems following earthquakes, and in particular, the requirements of NFPA 13: 1994 and NZS 4541 for the seismic bracing of sprinkler pipework.

The effect of the New Zealand Building Code and of Standard NZS 4512 on these issues is also discussed.

12.2 Standards for the seismic design of sprinkler systems in buildings

12.2.1

The current New Zealand Standard for Automatic Fire Sprinkler Systems, NZS 4541: 1996 had its origins in a provisional standard NZS 4541P: 1972, and subsequently evolved out of the more recent version NZS 4541: 1987 (including amendments of May 1989 and September 1991).

However, the requirements of NZS 4541 with respect to seismic design of sprinkler pipework in buildings have developed considerably since 1972, benefitting from the significant progress also made in recent years in the establishment of codes for the design of structures and emergency systems in buildings for seismic resistance. Standards NZS 4203: 1976 / 1984 / 1992 (Code of Practice for General Structural Design and Design Loadings for Buildings) and NZS 4219: 1983 / 1990 (Specification for Seismic Resistance of Engineering Systems in Buildings) are notable for their contribution.

Knowledge gained from recent earthquakes eg. Edgecumbe 1987, and the overseas events Loma Prieta 1989 and Northridge 1994, have also lead to changes to the requirements of NZS 4541 aimed at making increasingly more certain avoidance of significant damage to the sprinkler systems and permitting sprinkler systems to remain functional following an earthquake.

In this chapter the review of NZS 4541 starts with the current Standard and progresses back in time to explain the less demanding requirements of the earlier versions.

NFPA 13: 1994, Standard for the Installation of Sprinkler Systems, is a publication of the National Fire Protection Association (NFPA). It is accepted by the Authority Having Jurisdiction in New Zealand as an alternative to NZS 4541, and is used by sprinkler designers in this country, and particularly for property owners having US connections. Solomon (1994) provides the Formal Interpretations of the current Standard.

NZS 4219: 1990 notes that compliance with the seismic requirements of NFPA 13 is accepted as compliance with the requirements of NZS 4219 (reference to Section 2.16).

12.2.2

NFPA 13: 1994

In terms of seismic resistance of pipework the general requirements of this Standard as noted in Solomon (1994) is for sprinkler systems to be protected to prevent pipe breakage from shaking by:

- pipe stress avoidance through use of flexible fittings and clearances, and
- pipe bracing to maintain system alignment and prevent the development of damage-inducing momentums.

Explanations of other requirements and of terms generally in use in NFPA 13 are summarised in Section 4.0 of the Glossary of this report.

In evaluating the potential for damage to sprinklers, and as recommended in Solomon (1994), consideration should be given to the degree of lateral and upward movement permitted by the particular hanging arrangement.

12.2.3

Standard NZS 4541:1996

This is the current Standard. It specifically acknowledges that many areas in NZ are subject to moderately high seismic activity which must be considered in sprinkler design. Two reasons are given in the Foreword of that document:

1. To avoid inadvertent water leakage through pipe failure.
2. To recognise that earthquakes cause fires.

It makes the general requirement (reference Clause 104) for all components of the sprinkler system to be designed and installed so as to remain operational at the earthquake loadings specified in NZS 4203: 1992. Additionally, it requires (reference Clause 109) that the seismic resistance of sprinkler system pipework installed under the provisions of the superseded Standards of 1972 and 1987 be upgraded to comply with the seismic resistance requirements of the 1996 Standard, but subject to the seismicity of site locations (refer to s/s 12.2.6 of this report).

The support and bracing system which is to enable the sprinkler system pipework to resist seismic loads, is required to be configured by one of the following ways:

- by a first principles seismic design whose objective shall be to achieve a pipework system performance at least equal to that of the building structure under the earthquake loadings of NZS 4203, or
- on the basis of a prescriptive scheduling method as set out in the Standard.

Prescriptive scheduling method.

NZS 4541: 1996 defines the principles on which the prescriptive scheduling method for the design of the pipework support system is based. These principles are:

- a) Lateral supports are of sufficient stiffness to force piping to move with the immediate support structure.
- b) Lateral supports are spaced to limit pipe deflections under resonating dynamic load such that pipe joints and immediate vertical supports are not over-stressed.
- c) Lateral supports are ductile and fixings are designed over-strength.
- d) Stresses due to differential movements of building structures are minimized through the use of pipe flexibility or clearances.

The design level of seismic resistance of the sprinkler pipework is given as the repeated forces due to seismic acceleration of 1.0g acting on the mass of the pipework in any direction, in addition to the gravity force. In specifying this load, the Standard notes that it may be greater than the requirements of NZ 4203 and may increase the support size, but it eliminates the need for more detailed study.

The Standard defines the main aspects of flexibility, bracing and clearance in the installation of pipework, to achieve the required level of seismic resistance. These are summarised in Section 5.0 of the Glossary of this report.

12.2.4

Standard NZS 4541:1987

This superceded Standard (which incorporated Amendments No.1 and No.2) required all units of a sprinkler system to be designed and supported to resist earthquake loadings specified in NZS 4203 (the latter was the 1984 version). Compliance with Section 403.9 of NZS 4541:1987 was considered to achieve the required level of seismic resistance for pipework, but for other items of the sprinkler system the relevant sections of NZS 4219 were to be used (the latter was the 1983 version, but that Standard was amended in 1990).

Additionally, NZS 4541: 1987 required (reference Clause 109) that seismic resistance of sprinkler systems installed under the provisions of the superceded 1972 Standard be upgraded to comply with the seismic resistance requirements of the 1987 Standard, but subject to the seismicity of site locations (refer to s/s 12.2.6 of this report).

Section 403.9 of the 1987 Standard dealt with the design of pipe supports in a prescriptive manner by tabulating maximum spacings, maximum unsupported pipe length and minimum hanger diameters, against pipe size.

Bracing requirements were for earthquake induced movement in any direction, but the Standard exempted the bracing of pipes of less than 50 mm NB, or where movement relative to the building members was limited by U-bolts, clamps or by single rods less than 300 mm long. Where these conditions did not apply the sideways movement of hangers was to be prevented by four nominated methods: by clamping to the structure,

by fitting a rigid bracket, or by fitting two hangers in the vee formation, or by clamping side branches. Longitudinal bracing was to be provided with reference to NZS 4219.

12.2.5

Standard NZS 4541P:1972

This Standard incorporated the “Rules for Automatic Sprinkler Installations” published by the Fire Offices’ Committee in London. According to the Standard’s Introduction, it included amendments to New Zealand requirements. However, these dealt with issues of hydraulic design and sprinkler performance but not requirements for pipework support.

This latter aspect was covered by The Insurance Council of New Zealand Circular Number 606 and in particular specified the support and fixing of pipework under static loading. The seismic resistance of pipe runs and fixings appeared not to be considered at that time.

12.2.6

The development of sprinkler system seismic resistance requirements within NZS 4541

It is evident from each re-issue of NZS 4541 and particularly from the 1996 version, that significant developments have occurred in the requirements for the seismic resistance of pipe runs and fixings. These developments have drawn upon the knowledge gained from the practical application of the Standard, from recent earthquakes eg. Edgecumbe 1987, Loma Prieta 1989 and Northridge 1994, and the advances in design of seismic resistance of structures and emergency systems in buildings. These requirements are aimed at making increasingly more certain the avoidance of significant damage to sprinkler systems, to permit sprinkler systems to remain functional following an earthquake.

The Edgecumbe earthquake of 1987 is on record as having caused severe damage to sprinkler systems in many earthquake-damaged buildings (refer to Table 9.1 of this report). Voss (1987) noted that practically all the severely damaged systems had been designed to NZS 4541P:1972, and that the damage had been the consequence of:

- lack of adequate sway bracing
- rupturing of piping where differential movement could occur between respective parts of buildings to which it was attached
- failure of screwed joints in inadequately braced medium weight pipes also leading to the failure of screwed joints in range pipes through load re-distribution.

NZS 4541: 1987 was the first attempt at compliance with NZS 4203. However according to Voss, a decision as to how these requirements were to be achieved was left to the designer of the day, and that a determination of acceptable performance of an installed sway-bracing system could have been a matter of judgement and opinion.

For the design of sprinkler pipework restraint NZS 4541: 1996 provides the alternatives of either a first principles design (ie. a dynamic seismic analysis), or a design using the Standard’s prescriptive support and bracing schedule. Their aim is to achieve a level of sprinkler system seismic resistance that makes more certain such systems reliably provide their fire control function in the aftermath of an earthquake.

Both NZS 4541: 1987 and NZS 4541: 1996 provide clarification of the status of systems whose pipework seismic resistance has been designed to superceded Standards. The current requirements are as follows:

- sprinkler systems previously installed in compliance with NZS 4541P: 1972 or NZS 4541:1987, and which are located in areas of New Zealand designated by NZS 4203: 1992 as having a zone factor greater than 0.6, are to comply with the earthquake loadings specified in NZ 4203: 1992 or alternatively with the requirements of the prescriptive support and bracing schedule of NZS 4541: 1996.

The effect of the 1996 Standard is to require all new sprinkler systems to comply with the current requirements for pipework seismic resistance. The bracing of pipework of existing systems complying with superceded sprinkler standards and which are located in areas of New Zealand having a Z-factor > 0.6 are to be upgraded retrospectively, at the time of significant sprinkler alterations or at such time as the Authority Having Jurisdiction may require.

NZS 4203: 1992 defines the zone factor, Z, as an indicator of relative seismic hazard (refer to Volume 2, Commentary C4.6.2). In that Standard the values of Z are defined as being equivalent to the 450 year return period, elastic 5% damped uniform hazard contours for a structural period of 0.2 seconds. Values for Z have been limited to between 0.6 (applies near Dunedin and north of Hamilton) and 1.2 (applying at Whakatane). The map of zone factors as published in the Standard is depicted in Figure 12.1 of this report.

A callibration of Z in terms of peak ground acceleration is given in the Commentary to NZS 4203 (but is described as fairly approximate). This is stated as being about 40% of the value of Z giving the 450 year return period peak ground acceleration. As an example the Whakatane area (with $Z = 1.2$) the 450 year return period earthquake could be expected to produce accelerations of approximately 0.5g in the pipework. This can be compared with the NZS 4541: 1996 basis for prescriptive design as a pipework resistance to seismic forces at the stated and more conservative 1.0g seismic acceleration.

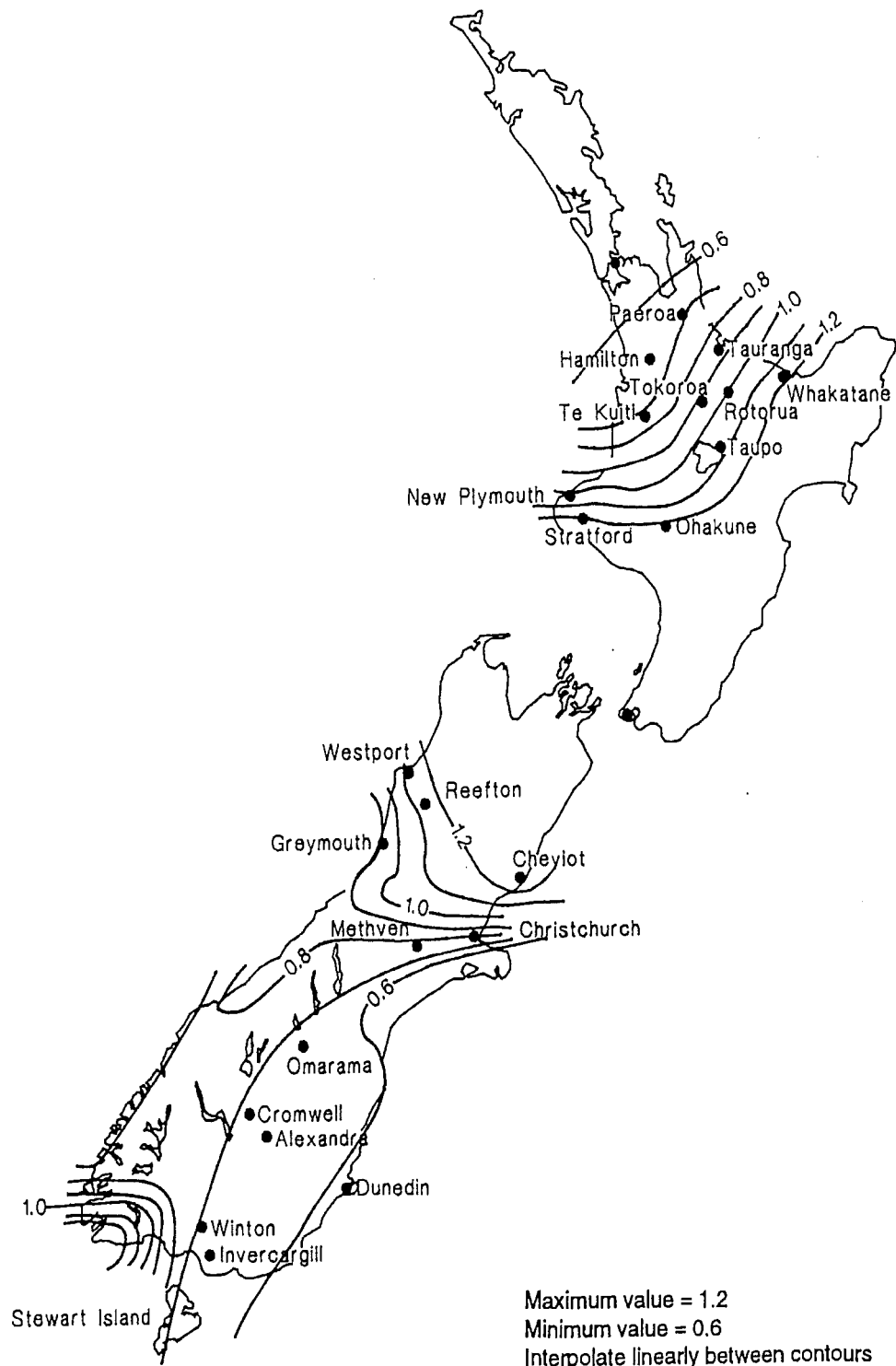
12.2.7

Seismicity and water supplies

Solomon (1995) made the general observation that any sprinkler system is only as good as its water supply, and the supply must be automatic and reliable. As noted in Chapter 10 of this report, past earthquakes have demonstrated the need for reliable post-earthquake water supplies for fire protection and the inevitability that underground reticulated water supply systems will suffer in strong ground shaking.

NZS 4541: 1996 includes restrictions (reference Section 601.5) on the dependency of sprinkler systems on town water reticulation systems in areas having a zone factor (as defined above) greater than 0.6.

Figure 12.1: Zone factor, Z
(Source - NZS 4203: 1992, Volume 1)



Under that circumstance the sprinkler system water supply is to be from a dual superior supply, consisting of both of the following:

- a primary supply, which shall be -
 - either a diesel engine-driven pump taking water from an approved source other than a town main (eg. storage tank, swimming pool, well or artesian bore, or open water, but in each case to be approved by the authority having jurisdiction)
 - or an elevated tank
- a secondary supply, which shall be -
 - either a town main, boosted town main or supplemented town main
 - or a diesel engine-driven or an electric motor-driven pump taking water from an approved source other than a town main
 - or an elevated tank.

The restriction in regard to a primary dependency on town water reticulations in areas of moderately high seismicity reflects the concern over the vulnerability of town water reticulations to strong shaking. The Standard does not require retrospective upgrading of the water supplies of existing systems complying with superceded sprinkler standards.

12.3 Standards for the seismic design of fire alarm systems in buildings

12.3.1

Standard NZS 4512: 1994 (Fire alarm systems in buildings) makes no reference to requirements for the seismic resistance of fixings for fire indicator panels, power supply units, battery boxes or other associated equipment of significant mass, which may be disturbed by even moderate earthquake shaking and lead to the loss in serviceability of the fire alarm system.

However, the Standard requires that control and indicating equipment pass a vibration operational test in accordance with Standard BS 2011, as a requirement for deemed compliance with NZS 4512: 1994.

Although not referred to in NZS 4512, the Standard NZS 4219 (1990) requires Communications Systems ie. cubicles, control panels (it is suggested that could be inclusive of fire alarm panels), cabling and the like, should be designed and installed generally in accordance with the requirements for electrical equipment, which is for secure anchoring to the floor or to the structure of the building or both, and braced where necessary to resist lateral forces. A prescriptive fixing schedule for lightweight equipment is given in that Standard.

12.4 New Zealand Building Code

12.4.1

The New Zealand Building Code Clause B1 requires buildings and building elements to “have a low probability of collapse or of causing loss of amenity” taking into account likely loading conditions (which includes earthquake and fire), and the consequences of failure. The Code (refer to Glossary in this report) defines buildings to include any

mechanical, electrical, or other systems whose proper operation is necessary for compliance with the Building Code.

The Approved Documents, being a means of compliance with the Building Code, call up New Zealand Standard NZS 4203 to provide for the determination of loadings and materials of construction, and Standard NZS 4219 for levels of seismic resistance of engineering systems in buildings. Those Standards were written for local conditions, and according to BIA News (1993) satisfy the Building Code provisions for likely loadings and low probability of failure.

12.4.2

The question of whether it is necessary for the fire safety provisions within buildings to remain effective following an earthquake was addressed in BIA News (1993). The BIA News is a periodical of the Building Industry Authority in which indications and guidelines are issued with the stated purpose of helping people to understand the legislation, but under a disclaimer advising that “binding interpretations of the Building Act and Regulations can be issued only by the courts”.

The BIA News confirmed that it is necessary for fire safety provisions to remain effective following an earthquake, but only to the extent of withstanding earthquake loads which are twice those required to bring the building to its Serviceability Limit State (SLS), which is defined in NZS 4203 as a loading condition which causes a building to become unfit for its intended use. Some minor damage may be expected at these levels of load, but according to BIA News that damage should be limited to non-structural elements and should be capable of being easily repaired. Building service, and passive and active fire protection measures, are expected to remain operative and all egress paths clear as the building deforms to loads of this level.

However, NZS 4203 requires “critical proprietary equipment” in buildings to be capable of withstanding the Ultimate Limit State (ULS) of the building, and this is expanded on in the paper Botting and Buchanan (1998). This requirement is expected to cover sprinkler systems and other active fire alarm systems.

12.5 Conclusions

12.5.1

This chapter discusses code requirements aimed at ensuring active fire protection systems in buildings survive major earthquakes and remain capable of protecting life and property.

12.5.2

The main issues are:

1. The seismic resistance provisions to be satisfied in NZS 4541: 1996 for the design of sprinkler systems are aimed at making increasingly more certain the avoidance of inadvertent water leakage through pipe failure, and sprinkler system serviceability for effective use in the control of fire after earthquake.

2. A general requirement of sprinkler codes is for the protection of sprinkler systems from breakage by shaking, and specifically
 - a). Pipe stress avoidance through the use of flexible fittings and clearances, including flexibility at building seismic separation joints to accommodate substantial relative motion.
 - b). Pipe bracing to maintain system alignment under both horizontally and vertically applied forces, and to prevent the development of damage-inducing momentums.
 - c). Pipe bracing attached directly to the building structure, and the fasteners and structural elements at the points of connection being of adequate capacity to handle the intended load.
3. Over the last 25 years significant developments have occurred in New Zealand in the requirements for the seismic resistance of sprinkler pipework and fixings. These developments have drawn upon the knowledge gained from the practical application of NZS 4541, from recent earthquake experience eg. Edgecumbe, Loma Prieta and Northridge, and from advances in the design of seismic resistance of structures and emergency systems in buildings.
4. By the current Standard NZS 4541: 1996, all components of new sprinkler systems are to resist seismic loads at the earthquake loadings specified in NZS 4203: 1992. For the pipework support and bracing of new sprinkler systems, design which achieves a performance that is at least equal to the building structure under the earthquake loadings of NZS 4203, or which adopts the prescriptive solution detailed in NZS4541 are deemed to satisfy the requirements of NZS 4541: 1996. The bracing system is also to provide seismic restraint of range pipes.
5. The bracing of pipework of existing systems complying with superceded sprinkler standards and which are located in areas of New Zealand having a Z-factor > 0.6 are to be upgraded retrospectively at the time of significant sprinkler alterations, or at such time as the Authority Having Jurisdiction may require.
6. The NZS 4541: 1996 requirement for Class A dual superior water supplies for new sprinkler systems in areas where Z-factor > 0.6 reflects the concern for the vulnerability of town water reticulations to strong shaking. The Standard does not require retrospective upgrading of the water supplies of existing systems complying with superceded sprinkler standards.
7. NZS 4203: 1992 requires critical proprietary equipment in a building to be capable of withstanding the Ultimate Limit State of the building without mal-function during a major earthquake. This is expected to cover sprinkler systems and other active fire alarm systems.

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CHAPTER 13.0

FINANCIAL IMPACTS OF LOSSES FROM FIRE FOLLOWING EARTHQUAKES

13.1 Background

13.1.1

There is much documented historical evidence of the horrendous effects in both human and financial terms of major earthquakes and post-earthquake fires.

Through the use of analytical modelling and empirical assessments the financial impacts of damage losses are quantifiable, and have been predicted for worst case conditions by investigators, for a number of locations with high seismic risk.

13.1.2

This chapter summarises and discusses fire damage loss values from studies individually described in Chapter 11.0 of this report.

Brief discussions are also provided on the role of insurance for obtaining financial relief from the impacts of post-earthquake fire, and on the benefits from achieving reduction in building risk exposure through provision of fire safety systems having performance and reliabilities appropriate to the risks.

13.2 Fire damage loss predictions

13.2.1

Cousins et al (1990)

The total loss (buildings and contents) due to fires triggered by a major Wellington fault event and affecting central New Zealand was assessed as NZ\$340 M by Messrs Cousins, Dowrick and Sritharan.

This was tagged with a standard deviation of \$140 M, and the expected ranges of actual loss and probabilities, given average climatic conditions, were expressed as follows:

- 70% probability of being between \$200 M and \$480 M
- 95% probability of being between \$60 M and \$620 M.

The standard deviation accounted for the statistical uncertainties associated with the following conditions, as noted by the authors:

- number of post-earthquake ignitions
- location of ignitions
- timing of ignitions
- climatic conditions
- availability of fire-fighting resources.

They predicted that given adverse climatic conditions the loss figures could be nearly doubled.

For comparison, the expected loss due to shaking from the same earthquake was given as about \$5 B, ie. 15 times the fire loss.

The estimated fire losses from the Subduction zone and Wairarapa fault events also studied by the authors were stated as \$340 M and \$430 M respectively.

13.2.2

Scawthorn & Khater (1992)

The Scawthorn and Khater 1992 studies gave the assessed mean loss due to fires following a San Andreas fault movement as US \$7.3 B (about 1% of the assessed value of total property at risk, including contents, stated as \$ 655 B) (Refer to Table 11.4 of this report).

13.2.3

Hopkins (1995)

The estimated total Regional consequential fire loss from D.Hopkin's studies of property damage from the Wellington fault event was \$56.7 M, aggregated from the following stated values:

• Wellington City	\$39.8 M
• Hutt City	\$10.5 M
• Upper Hutt	\$3.0 M
• Porirua	\$3.4 M
• <u>Regional</u>	<u>\$56.7 M</u>

It will be noted that the Regional post-earthquake fire loss estimate of \$56.7 M is almost at the lower end of the 95% probability range (ie \$60 M - \$620 M) for loss as estimated by Cousins et al.

As assessed by Hopkins, the total value of property at risk (ie.replacement value) and including contents was \$48.5 B; the cost of overall damage ie.due to shaking and post-earthquake fire was \$7.8 B.

Hopkins noted that the overall damage value as a percentage of the total assets at risk (16%), while significant, is unlikely to undermine overall confidence in the city's future. This is borne out from experience from passed earthquakes overseas which demonstrates that earthquake damage, while horrendous, has not lead to significant relocation of people and assets.

13.3 Financial impacts and relief

13.3.1

The financial impact of a damaging event on a property owner or a business can be significantly influenced by decisions made at some prior time as to how the risks of loss are to be controlled.

Jensen (1975) noted that loss control can take three forms as follows, although in practice owners use a combination of these techniques:

- a risk can be assumed and its consequences accepted if it occurs
- it can be transferred to some other risk bearer, such as an insurance company
- a protection system can reduce or possibly eliminate the source of the risk.

Insurance is a pooling of risk, with many individuals paying relatively small amounts in advance to cover the large losses of a few. Protecting businesses and individuals from large economic losses due to the impact of earthquakes, and other natural disasters, is one of the major functions of normal insurance underwriters.

Walker (1994) noted that a major risk management task for insurance companies is protecting themselves from excessive losses arising from catastrophic events of this nature. Since losses from a single catastrophic event can be many times the annual average losses sustained, and premiums collected, by an underwriting company, it is generally not feasible for insurance companies to carry the whole risk themselves through accumulated reserves. Reinsurance is used instead, and through this the risk is spread across the worldwide insurance industry.

However, sale of earthquake insurance is limited by the ability of the insurance market to supply adequate capacity. Roberts (1994) noted that since 1990 reinsurance companies have suffered heavily in the wake of a succession of catastrophic events. Some major reinsurers have discontinued underwriting risks while others restrict their exposure to well defined limits.

The premium pool in New Zealand is a tiny part of the worldwide insurance premium pool, yet according to Lifelines (1993) New Zealand has some of the world's highest aggregations of earthquake risk (particularly in areas like Wellington's CBD) and insurers must go to international reinsurance markets to buy their earthquake protection.

13.3.2

Post-Earthquake Fire Insurance in New Zealand

The Earthquake Commission Act 1994 effectively de-regulated Natural Disaster insurance and mandated that type of insurance cover with the purchase of fire insurance for residential buildings, but not for commercial (ie. non-residential) risks. Under the Act, earthquake and fire occasioned by earthquake are perils included under "Natural Disaster".

Lifelines (1993) noted that the Earthquake Commission (EQC) provide the Natural Disaster insurance cover on residential building risk for replacement value up to \$100,000, and up to \$20,000 for personal property.

The provision of non-residential Natural Disaster cover by the EQC was phased out by the Act, and effectively from January 1997 the insurance market was expected to provide the capacity to fill that gap. This capacity will usually come from international reinsurance markets but insurers are dependent on obtaining it at an affordable price.

However, non-residential property is no longer required to be insured against earthquake, and fire occasioned by earthquake. Lifeline (1993) suggested that the de-regulation of earthquake insurance does provide some flexibility to commercial property owners in terms of risk management in the event of a major disaster, while the insurance industry can impose its discipline of rewards and penalties relative to the owner's management of his earthquake risk.

An issue of practical significance after an earthquake, and which is noted in Section 15.4 as an area for further research, is if the Fire Service is able to provide independent verification of whether a fire has resulted from the earthquake, or is a fire caused by other means?

13.3.3

Post-earthquake Fire Insurance in United States and Japan

In the high seismicity western United States almost all home-owners are insured for fire, which includes fire caused by earthquake shaking. However, according to Scawthorn and Khater (1992), only about 20% of home-owners in California carry additional special coverage for earthquake shaking even though California law requires insurers to offer shake coverage to property owners. It was thought that a similar proportion of commercial property owners purchase specific coverage for shake damage.

Fire losses predicted by the Scawthorn and Khater 1992 study are substantially higher than the insured shake damage losses. They cited a California Insurance Department study indicating US \$6B for insured shake damage in the San Francisco Bay area compared with US \$7.3B predicted fire damage loss.

EERI (1985) raised the solvency implications of certain insurance companies, or even the industry, under the impact of major fire damage losses such as those predicted by the worst case scenario in the San Francisco Bay area. Another aspect of this in the United States is the perhaps small but real potential for arson following earthquake, by property owners whose damaged risks are not covered by earthquake insurance.

In Japan fire following earthquake is not covered under dwelling or other common forms of insurance. Special earthquake riders are available on dwelling insurance, but are not commonly bought. Walker (1995) noted that the insured property losses from the Kobe earthquake were between US\$5 - 7 B, which was a low value relative to the total losses estimated as US\$65 B, and reflects the low level of earthquake insurance due to its high costs and limited cover.

According to Walker the pattern of Kobe earthquake damage clearly showed that damage was selective. New buildings located anywhere, and most buildings on firm ground, performed well. These buildings would have been insurable on a selective basis. He referred to the development of sophisticated computer models for estimating insurance risk and the possibility of treating catastrophe insurance on a selective basis.

He predicted that not only will this create new opportunities for insurance, such as in Japan, but will also lead to more tangible incentives for improving the earthquake resistance of high risk buildings.

13.3.4

Improvement of Risk by means of Protection Systems

The cost of insurance is likely to depend on the insurance company's assessment of existing property risk. Jensen (1975) noted that fire insurance requirements have exerted a strong influence on fire protection expenditures. Insurance rating practices, which offer reductions for certain features eg. building-wide sprinkler systems, and penalty charges for others eg. low levels of fire resistive construction, directly affect the owner's costs for insurance.

In the same manner the lower rates for properties that meet the fire protection standards of the "highly protected risk" encourages owners to provide higher levels of reliability in their fire safety systems eg. dual fire sprinkler system water supplies, very early warning smoke detection systems, 24 hour on-site alarm monitoring systems etc., and greater levels of seismic resistance in the associated plant and equipment.

13.4 Conclusions

13.4.1

This chapter addresses the financial impacts of losses from post-earthquake fire. It identifies the opportunities available for reducing the effects of post-earthquake fire through the provision of fire prevention and fire protection measures to control building risk exposure, and for reducing their financial impacts through the mechanism of insurance.

13.4.2

The main issues are:

1. Information about past earthquakes indicate the potential for enormous financial impacts from earthquake damage, and from the losses from fire following earthquakes. Analytical modelling of fire effects and empirical assessments of the fire losses help in the prediction of damage losses from future earthquake events.
2. The impacts of post-earthquake fire losses are borne by the private and public sectors, and span from the individual property owner to international reinsurance markets. In the built urban environment the opportunity for reducing building exposure to the risk of fire following earthquake can be taken through the provision of adequate earthquake resistance in buildings, plant and equipment, and through the provision of fire safety systems having performance and reliabilities appropriate to the fire risks. However, property owners basically have the choice as to how the risks of earthquake and fire losses are to be managed in their buildings (although some safety systems may be mandatory depending on the way in which, and by whom, the property is used).

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CHAPTER 14.0

POST-EARTHQUAKE FIRE DAMAGE MITIGATION MEASURES

14.1 Background

14.1.1

New Zealand's position as a landmass on the earthquake-prone Pacific rim places it at extreme risk to potentially damaging earthquake fault line events. Of special concern are the large population centres within areas of New Zealand of high relative seismic hazard, especially the Wellington Region.

There is prolific evidence from which to predict the consequences of major earthquakes, but simply stated these are shaking damage and fire damage. While this suggests that mitigation of damage losses may come from measures which address separately the two generic areas of building earthquake safety, and building fire safety, there is also a common, overlapping area within which each requires the benefits of the other.

Interactions between fire protection and earthquake protection are most important if the fire safety systems are to continue to function after an earthquake, to ensure the best possible outcomes in the control of damage and financial losses to building owners and to insurers.

14.1.2

In this chapter measures are identified which can be taken by building owners and tenants, property and risk managers, insurers and fire engineers, territorial authorities, the Fire Service and others, for the control of post-earthquake fire losses. These are then discussed and prioritised.

14.2 Measures to mitigate post-earthquake fire damage to buildings

14.2.1

Suggested measures for the mitigation of post-earthquake fire damage to buildings are provided in Table 14.1.

14.3 Discussion on mitigation measures

14.3.1

Ignition sources

An assessment of potential fire ignition sources for adequate seismic restraint is particularly relevant to unattended electrical equipment, gas and electric heating and cooking appliances. Heavy equipment items should be anchored to resist lateral loads with a restraint system specified by a structural engineer.

Table 14.1: Measures to mitigate post-earthquake fire damage to buildings.

Mitigation area	Mitigation action
1. <u>Ignition sources</u>	Assess potential fire ignition sources in buildings for adequate seismic restraint, and control by bracing or anchoring.
2. <u>First aid fire-fighting</u>	Provide equipment appropriate to the fire hazards in buildings, and ensure operator competency in its use through training of occupants.
3. <u>Earthquake safety</u>	Have building surveys undertaken to assess the adequacy of buildings' seismic capacity, and of the seismic resistance of engineering systems. Implement strengthening programmes for high risk buildings and the observation of modern earthquake resistive building practices. These programmes will take into account the requirements of the territorial authority and the risk management objectives of building owners.
4. <u>Sprinkler systems</u>	Increase the reliability of sprinkler systems by ensuring the adequate seismic capacity of all components, and secure water supplies.
5. <u>Passive fire protection</u>	Survey buildings for resistance to spread of fire, and provide separations to satisfy Code life safety requirements and the building owners' fire safety objectives for the protection of property and building function.
6. <u>Smoke control systems</u>	Survey the extent of seismic resistance of installed smoke control systems and built-in equipment in buildings for assurance of full functionality after earthquake shaking.
7. <u>Fire brigade response</u>	Reduce the risk of impaired fire brigade response to post-earthquake fire outbreak through measures to: <ul style="list-style-type: none"> - protect garaged fire-fighting vehicles and equipment during earthquake shaking - secure the serviceability of fire-call response and despatch systems through damage from earthquake shaking - ensure resources to permit brigade draw-off from alternative fire-fighting water supplies
8. <u>Urban water supplies</u>	Reduce the risk of post-earthquake fire damage and property losses by developing better means to ensure the continued availability fire-fighting water supplies. Measures could include the strengthening of below-ground reticulations and critical facilities above ground against earthquake damage, and establishing alternative fire-fighting water sources such as additional storage capacity in high risk areas.
9. <u>Restoration of utility services after earthquake</u>	Reduce the risk of extended fire damage and property losses due to ignitions during the re-instatement of electricity and gas supplies, through co-ordinated efforts of the utilities, emergency rescue and recovery services, and the Fire Service.
10. <u>Fire-resistant urban environments</u>	Town planners can reduce the risk of major post-earthquake fire losses by providing in city and regional schemes for the development of fire-resistant urban environments as part of the urban renewal process, and relief from the fire hazard caused by high concentrations of buildings with combustible claddings. This can be achieved through buildings of non-combustible claddings, and by providing wide roadways, parks, and other open spaces.

Building gas services and appliances can be fitted with valves that automatically shut off gas supplies in the event of an earthquake, or valves that close in the event of a sudden pressure drop such as results when a supply line ruptures. In each case the valve eliminates a source of fuel, and potentially, a major fire. These devices are available in the United States but their availability and suitability to New Zealand conditions need clarifying with the NZ Gas Industry, and the economics identified. Gas feeds should be fitted with flexible connections between the gas pipe and the equipment, and pipe runs near equipment should be re-routed to avoid potential impact.

14.3.2

First aid fire-fighting resources

The provision of first-aid fire-fighting resources ie. fire extinguishers or fire water hose reels permit fires to be manually extinguished by citizens at an early stage without fire brigade assistance, and as an independent fire prevention measure especially in the event of impaired brigade response.

Extinguishing fires at an early stage will be part of the building fire safety objectives under normal circumstances, but the equipment should also be available and remain effective following earthquake shaking.

14.3.3

Earthquake safety

The seismic resistance of engineering systems in buildings (including the active fire protection and alarm systems) can only be as good as the seismic capacity of the building itself.

Unless the building is considered by the territorial authority as a high risk building to be included in a mandatory seismic strengthening programme, the extent that a building should or is to be strengthened is a risk management decision of the building owner.

The factors considered in taking a decision will likely include:

- value of the building and/or its contents
- functional importance of the building particularly if it is a commercial property
- expected remaining serviceable life of the structure.

In New Zealand commercial property owners will need to consider how they will protect their businesses in the event of a major disaster such as earthquake, since there is no requirement for them to carry insurance against earthquake, or fire occasioned by earthquake. A decision in terms of risk management will need to consider the increased use of protection systems for fire, and for seismic resistance in associated plant and equipment. This is an example of the overlap between building earthquake safety and building fire safety referred to in the Background comments to this chapter.

14.3.4

Sprinkler systems

Sprinkler systems are intended to provide the means, in the absence of manual extinguishment, for fires to be controlled or suppressed automatically at an early stage.

Fire protection and earthquake protection need to interact if fire safety systems are to continue to function after an earthquake. For reliable sprinkler system performance in the aftermath of a major earthquake seismic restraint of system components, pipework and on-site water storage is essential, through adequate interpretation of NZS 4541: 1996.

While sprinkler pipework should be held rigidly to the building by hangers, sway braces and anchors to provide restraint under seismic load they should also have sufficient flexibility (provided through pipe flexibility or by the use of flexible couplings) to prevent over-stressing of the bracing and support system. Flexibility should also be provided where pipework crosses structural separations. Clearance is necessary to prevent breakage due to building movement and should be provided around all piping extending through walls, floors and foundations, with the annular space around piping penetrations through fire-rated assemblies filled with an appropriate fire-stopping system.

To ensure the availability of water in the event of loss of town main water supplies due to earthquake damage, provision should be made for primary fire-fighting water from an on-site stored supply and associated diesel engine-driven pump.

14.3.5

Passive fire protection

For unsprinklered buildings (or in the event that a sprinkler system fails) passive fire protection systems provide the fall-back fire safety elements to reduce the risk of fire spread and fire losses beyond the fire compartment, if initial first-aid fire attack fails.

While the particular passive fire protection treatments applied (apart from those which are mandatory for life safety) will have regard to the fire risk management objectives of the building owner, they will generally include the following:

- structural fire protection
- compartmentation of occupied spaces into functional areas by means of fire-resistant separations
- maintaining the fire-rating of fire separations where they are penetrated by services, by means of through-penetration protection systems
- maintaining fire separations between floors of multi-storied buildings
- treatment of breaches in fire separations such as at seismic gaps and construction joints, in services risers and communicating voids, and gaps between floor perimeters and curtain wall construction on multi-storied buildings.

14.3.6

Smoke control systems

Smoke control by pressurisation and venting may be part of the building fire safety objectives under normal circumstances, but the equipment should also be available and remain effective following earthquake shaking.

These are areas of specialist design, drawing on both Fire Engineering and Mechanical Engineering knowledge, and where these systems are installed specific assurance needs to be gained that their seismic resistance satisfies the Loadings Standard.

14.3.7

Fire brigade response

Damage to garaged fire-fighting vehicles and equipment due to earthquake shaking of fire station buildings has been noted in a number of earlier earthquake reports. Loss of serviceability of fire-call response and despatch systems due to shaking damage has also been reported.

However, there is much evidence available from accounts of the effects of fire on the built urban environment following major earthquakes to indicate that the extent of property damage is significantly affected by the inability of fire brigades to access firegrounds, and to obtain fire-fighting water to suppress fire or contain fire spread.

Given that evidence, it is likely that property owners, insurers, territorial authorities etc. located in areas of New Zealand having high seismic risk would have considerable interest in the extent that fire brigade actions can be expected to mitigate the risk of fire losses to their property.

Questions covering aspects of fire brigade response are noted in Section 15.4 of this report as areas for further research.

14.3.8

Urban water supplies

Water supply is a critical factor in controlling fire damage and losses.

There is much evidence available from the reports of major earthquakes to indicate that underground water distribution systems are very vulnerable to earthquake shaking. Failures of some systems can be expected even in moderate earthquakes. As the absence of water at hydrants can severely hamper fire-fighting operations, territorial authorities and fire brigades could reduce the risk of post-earthquake fire damage and property losses by developing better means to ensure continued fire-fighting water supplies.

Programmes for structural improvements to below-ground reticulations, suggested in sources referred to in this report, include the replacement of cast iron and asbestos cement pipes in vulnerable areas with ductile pipe systems, the strengthening of pipes and joints, and the introduction of flexible connections.

Other improvement works that have been suggested are:

- the strengthening of critical facilities such as tanks and pumping stations
- the anchorage and bracing of plant such as pumps, standby power facilities, and of control facility equipment
- installing seismic shut-off valves at reservoirs (but provide procedures and access for re-opening for fire-fighting)
- establishing special hydrants with large diameter connections specifically for refilling Fire Service tenders.

Alternative water sources that have been used for fire-fighting following an earthquake include shallow wells, rivers, seawater pumping from harbours, and additional storage capacity in cisterns or in temporary above-ground tanks.

Questions addressing the extent that operational procedures and safeguards are being taken by water utilities are noted in Section 15.4 of this report as areas for further research.

14.3.9

Restoration of utility services after earthquake

The restoration of gas and electricity supplies following an earthquake places at odds the desire to restore utility services as quickly as possible and the desire not to cause additional fires.

In addition to a co-ordinated effort between the different utilities and the emergency rescue and recovery services during the re-instatement of supplies, the risk of extended post-earthquake fire damage and property losses due to ignitions could be further reduced by the following additional measures:

1. Techniques or instrumentation developed for use prior to the restoration of electrical service, to ensure that electricity is not restored to damaged structures or areas with natural gas leaks.
2. Restoring service only after individuals are present in every structure, with public officials authorised to enter structures where owners are absent, in order to check for fire, or gas leaks.
3. Fire units standing by in the area at the time of utility restoration.

14.3.10

Fire-resistant urban environments

Seismic strengthening programmes for high risk buildings reduce the likelihood of damage to buildings by earthquakes, and when combined with fire-resistive methods and materials in building construction and cladding, the risk of major fires occurring and of fire spread after earthquake shaking is reduced.

14.4 Mitigation priorities

14.4.1

Table 14.2 identifies a division and prioritisation of the suggested mitigation measures. The division is over the three categories of Building Owners, Territorial Authorities and the Fire Service, although the measures may also apply to other groups. Since territorial authorities are building owners, they will also have an interest in the measures for the reduction of building losses from post-earthquake fire as listed under Building Owners.

A prioritisation of the mitigation measures under each category is also suggested, with initial emphasis on those measures whose application is likely to be more easily achieved and at lower cost than measures lower in the lists.

Table 14.2: Suggested prioritisation of post-earthquake fire damage mitigation measures under three ownership categories.

Building Owners	Territorial Authorities	Fire Service
1. Control <u>ignition sources</u> in buildings by providing them with effective restraint against shaking.	1. Develop better means to ensure continued availability of <u>fire-fighting water supplies</u> by: - strengthen below-ground reticulations, and critical facilities above ground, against earthquake damage - establishing alternative fire-fighting water sources in high risk areas.	1. Declare the <u>role of the New Zealand Fire Service</u> , and its operational preparedness, for response to a major earthquake under a large population centre.
2. Provide <u>first aid fire-fighting equipment</u> in buildings and operator training for reduced dependence on the fire brigade.	2. <u>Co-ordinate</u> the efforts of the utilities, emergency rescue and recovery services, and the Fire Service during the <u>re-instatement of electricity and gas supplies</u> , after earthquake.	2. Reduce the <u>risk of impaired response</u> to post-earthquake fire by : - protecting vehicles and equipment, and fire-call response and despatch systems from shaking damage - ensuring the availability of equipment for draw-off from alternative water supplies.
3. Ensure <u>reliable sprinkler system performance</u> following earthquake through adequate seismic resistance of pipework and a secure water supply.	3. Provide in city and regional schemes for the development of <u>fire-resistant urban environments</u> and achieve through buildings of non-combustible claddings, and by providing wide roadways, parks, etc.	
4. Ensure <u>reliable smoke control system performance</u> following earthquake through adequate seismic resistance of smoke control plant and equipment.		
5. Ensure <u>spread of fire and smoke</u> in buildings is prevented by fire-resistant separations, smoke seals etc.		
6. Commission surveys for the assessment of <u>building seismic capacity</u> , and the <u>seismic resistance of engineering systems</u> . Implement strengthening programmes for buildings and equipment at risk to shaking.		

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CHAPTER 15.0

CONCLUSIONS AND RECOMMENDATIONS

15.1 Introduction

15.1.1

In order to confine a potentially expansive subject, the discussion in this project report is developed on three levels, as follows and in the order given:

1. A consideration of the dynamics of fire in buildings under normal conditions, and the standard fire protection responses to it.
2. An analysis of fifteen major earthquakes to discover the sequence of events and responses to fire in the aftermath of major earthquakes, but for each event addressing in particular the five areas of ignition sources, fire spread mechanisms, building fire safety system performance, viability of public water supplies, and fire brigade response to the fire challenges of the disaster.
3. A discussion of candidate post-earthquake fire damage mitigation measures.

15.1.2

This chapter presents a summary of what was learnt from the project, provides suggestions as to what we can do to reduce the impact of post-earthquake fire on the urban built environment, and concludes with details of areas for further research.

15.2 What was learnt from this project?

15.2.1

The main issues are described under the following headings:

1. Reality of fire following earthquake.
2. Post-earthquake fire ignition sources.
3. Fire development and damage potentials
4. Responses to building fires.
5. Role of passive fire protection systems.
6. Fire protection of building structural frames.
7. Earthquake damage to passive fire protection systems.
8. Earthquake damage to active fire protection systems.
9. Efficacy of water for automatic fire suppression systems.
10. Reliability of active fire protection systems.
11. Impairment of fire brigade response.

1. Reality of fire following earthquake.

There is much historical evidence to confirm the potential for earthquake shaking to initiate fires in the built urban environment. The horrendous outcomes in terms of losses of life and property were re-emphasised dramatically in the most recent Northridge and Kobe earthquakes. A correlation between fire ignition rates and earthquake intensity has been established for post-earthquake fires in the United

States (by Scawthorn in 1986), and has been used subsequently in several analytical models for estimating the magnitude of post-earthquake fire losses (by Cousins et al in 1990, and Scawthorn and Khater, in 1992).

Empirical data used for establishing these types of model must relate to the urban area, region and country under investigation. These requirements therefore limit the general utility of models already established for specific urban environments in Western United States, and in Japan. Their application as fire loss models to New Zealand or other regions with significant post-earthquake fire risk therefore need to reflect the specific local conditions and experience data, but this may well be difficult in New Zealand through the lack of quantified and confirmed data in respect of major issues, such as fire ignition sources and fire initiations, water supply functionality etc. in relation to past earthquakes.

2. Post-earthquake fire ignition sources.

Post earthquake ignition sources are primarily electrical or gas-related in nature, but also include open flame, hot surfaces, exothermic chemical reactions from spilled chemicals, and fires intentionally lit. It is not possible to eliminate all initial, or incipient, fire outbreaks following a major earthquake, but the risk of these may be reduced by some fire preventative practices. Restoration of electricity and gas supplies to damaged appliances, wiring or lighting fixtures, can cause ignition of combustibles in contact and ignition of leaking gas.

3. Fire development and damage potentials.

The fire conditions determining the fire's potential to destroy or damage a building, the contents and adjacent property, are the maximum fire temperature reached and the time for which the maximum temperature persists (resulting from the fire burn rate and the duration of burning respectively). Fire temperature and hence damage is increasing during the fire growth period and maximises during the fully developed burning stage.

The window of opportunity for effective fire loss reduction therefore progressively diminishes during the fire growth period and is lost totally at the transition to fully developed burning. Risk of failure of structural members or fire separations begins after the fire has reached its fully developed phase, and exists during its decay phase. Items of property whether structural or contents, need not be totally burnt in order to have lost all value.

4. Responses to building fires.

Under normal circumstances responses to building fires may be by a combination of fire protection systems in place in buildings, both active and passive, and manual fire-fighting by a fire brigade. If automatic sprinkler systems are present they will generally achieve containment of fires at an early stage of fire development, while fire brigades are capable of containing major fires to limit spread. In each case adequate water supplies need to be available, as experience demonstrates the impracticability of stopping fire spread without water. However, urban underground water distribution systems are very vulnerable to earthquake shaking and failures can be expected even in moderate earthquakes. With the absence of water at hydrants and where alternative water supplies have not been available, post-earthquake fires have been able to rage uncontrolled after some earthquakes and contribute to conflagration.

5. Role of passive fire protection systems.

The major role of passive systems in building fire safety is to provide barriers to the spread of smoke and heat. This is the “fail safe” protection which is available under normal circumstances even if other fire counter-measures are ineffectual. However, the success of a passive system depends on burnout or extinguishment of the fire occurring before its effectiveness degrades in a fire and is lost.

6. Fire protection of building structural frames.

The role of the structural frame of a building in fire safety depends on the type of building under consideration and on the desired level of fire safety. A structure may have a major role during and after the fire, and it may be unacceptable for the building to collapse in even the largest foreseeable fire eg. because evacuation is a lengthy process, or the building or its contents have great value, or safety of neighbouring buildings would be endangered. Alternatively, the structure may have virtually no role after a fire eg. because it can be readily evacuated, or no value is placed on the building, or no harm is brought to adjacent buildings.

7. Earthquake damage to passive fire protection systems.

The structural and non-structural damage caused to buildings by earthquakes can lead to the loss of integrity of passive protection systems. Structural fire protection systems are not tested for earthquake movement, but they have to be tough enough to remain in place during large deformations in fire resistance tests, which means that they will have some ability to accommodate movement from earthquake. However, if this is exceeded their passive protection can be damaged by cracking, buckling or breaking, and the openings created can permit the increased ventilation of compartment fires. Openings also allow uncontrolled migration of smoke and hot gases internally to other areas of a building. Additionally, if automatic or manual fire suppression is delayed, the fire resistance of structural members is likely to be challenged.

The need, especially in tall buildings, to contain fire by fire compartment boundaries and to prevent structural collapse, is paramount for occupants exiting, and for fire-fighters accessing effected areas to control a growing fire and prevent fire spread.

8. Earthquake damage to active fire protection systems.

In many cases following strong shaking the installed detection, alarm, and suppression systems may also be unreliable. This could be due to a number of factors including the activation of smoke detectors over a wide area due to the dust raised by shaking, or the dislodgement of detectors or control panels, or damage to their circuitry, or to the fire alarm wiring through structural damage. This may result in ignitions being undetected for a long period of time, and in large fires which are more difficult to extinguish.

9. Efficacy of water for automatic fire suppression systems.

“Suppression” are the measures taken to contain fire spread to within the enclosures of fire origin, and to the point where manual extinguishment can be undertaken. Fire sprinkler systems and water spray systems are the most efficient means currently available for suppressing fires by the use of water in most types of occupancies because they operate when the fire is small and only over the area affected by fire. The fire brigade may still be required to attend but it is unlikely to need to deploy the same amount of resources as in the case of fire in unsprinklered buildings.

Even in cases where sprinklers will not suppress the fire the cooling ability of water spray can protect structural elements of a building containing the fire, until the fire is manually extinguished.

10. Reliability of active fire protection systems.

The probability of all active fire protection systems working after a major earthquake is remote due to the likelihood of structural and non-structural building damage disabling the fire protection systems, water supply failure and power supply failure. On-site water storage or backup power for booster pumps are not compulsory and vulnerability therefore varies from building to building. Although the vulnerability of building sprinkler systems to earthquake shaking has reduced in recent times with the development of standards for the effective seismic design of systems, inadequate interpretation of the requirements can result in major sprinkler system damage eg. as seen after the Edgecumbe earthquake.

11. Impairment of fire brigade response.

Following a major earthquake, the response of fire brigades to citizens' requests for emergency assistance is likely to be impaired due to a number of reasons, including reporting delays caused by the failure of communications systems, loss of operational availability of vehicles and equipment caused by earthquake damage to Fire Service premises, and impassable access routes or traffic jams. Reduced or exhausted water supplies due to earthquake damage to buried water distribution networks or draining of unprotected reservoirs, will also impair fire-fighting effectiveness at the fireground. Likelihood of multiple simultaneous ignitions and insufficient fire brigade resources for the number of fires ignited at the same time by the earthquake will delay fire brigade attendance, and because they are not responded to in time may give fires the opportunity to grow and spread over large areas.

15.3 What do we do?

15.3.1

Mitigation measures

The section provides a summary of the measures which can be taken to reduce and prepare for fire losses in urban building stock due to the initiation, growth and spread of fires following earthquakes. The mitigation measures are discussed under the following headings:

1. Fire initiation and spread.
2. First aid fire-fighting equipment availability.
3. Post-earthquake restoration of utility services.
4. Seismic resistance of active fire protection systems.
5. Security of sprinkler water supplies.
6. Fire-fighting water supplies.
7. Fire Service response.
8. Post-earthquake fire loss modelling.
9. Fire-resistant urban environments.

1. Fire initiation and spread

Overall post-earthquake fire objectives should be to reduce the number of ignitions, and to reduce the likelihood that fires will spread. Therefore, reduce the risk of initial fire outbreaks following a major earthquake by applying installation procedures to heaters, stoves, fuel lines and fuel tanks etc, which achieve effective restraint against shaking. Additionally, the restoration of barriers to their full fire resistance ratings through attention to the fire-rating of those elements which compromise barriers' fire and smoke control performance, represent opportunities for effective fire loss control.

2. First aid fire-fighting equipment availability.

Provide first aid fire-fighting equipment in buildings and operator training, for reduced dependence on the fire brigade, especially in the event of impaired brigade response.

3. Post-earthquake restoration of utility services.

Develop procedures to ensure the efforts of the electricity and gas utilities, emergency rescue and recovery services, and the Fire Service, are co-ordinated during the reinstatement of electricity and gas supplies after earthquake, to avoid new fire ignitions.

4. Seismic resistance of active fire protection systems.

Increase the reliability of automatic fire alarm and sprinkler systems' performance following an earthquake by providing adequate seismic resistance to cabinets, panels, sprinkler components and pipework. The seismic resistance provisions to be satisfied in NZS 4541: 1996 for the design of sprinkler systems are aimed at making increasingly more certain the avoidance of inadvertent water leakage through pipe failure, and the assurance of sprinkler system serviceability for effective use in the control of fire after earthquake.

5. Security of sprinkler water supplies.

Reduce building sprinkler system dependence on townmain water supplies by providing on-site stored water and diesel engine driven pump(s) as the primary supply in earthquake at-risk areas. The requirement of NZS 4541: 1996 for Class A dual superior water supplies for new sprinkler systems in areas where the zone factor, $Z > 0.6$, reflects the concern for the vulnerability of town water reticulations to strong shaking.

6. Fire-fighting water supplies.

Increase the availability of fire-fighting water from urban water systems following major earthquakes, through structural improvements to these systems which include the replacement of cast iron and asbestos cement pipes in vulnerable areas with ductile pipe systems, the strengthening of pipes and joints, and the introduction of flexible connections. Establish alternative sources of fire-fighting water in high risk areas.

7. Fire Service response.

Increase the extent that NZFS station buildings and operational infrastructure are protected from the effects of earthquake damage by ensuring buildings have adequate seismic capacity, and critical contents are restrained to resist shaking damage.

8. Post-earthquake fire loss modelling.

To assist planning, preparation and response in New Zealand to fire following earthquake, quantify the potential for future fire damage in earthquake-prone urban areas by applying fire loss modelling to New Zealand conditions.

9. Fire-resistant urban environments.

Plan for the development of fire-resistant urban environments in city and regional schemes, as part of the urban renewal process and relief from the risk of major post-earthquake fire losses caused by high concentrations of buildings with combustible claddings. Achieve this through buildings of non-combustible claddings, and by providing wide roadways, parks and other open spaces as natural fire breaks.

15.4 What should be done in the future?

15.4.1

Areas for further research.

The following areas have been identified for further research, and details are provide in subsequent sections:

1. Fire brigade response.
2. Urban water supplies.
3. Urban macro-scale fire protection.
4. Development of an analytical model simulating post-earthquake fire ignition sources and the impact of control actions.

15.4.2

Fire brigade response

The main issue is the question:

“What is the declared role of the New Zealand Fire Service (NZFS) and its operational preparedness for response to a major earthquake under a large population centre (eg. after the “Wellington Fault Event”)”.

Specific areas of interest would be:

1. The priority to be given to fire-fighting, as opposed to the other likely (non-fire) demands on fire brigades eg. light and heavy rescue, hazardous materials incidents, vehicle accident response, property salvage etc.?
2. The effectiveness of current operational strategies and equipment for the sourcing of fire-fighting water, given that underground reticulated supplies are likely to be damaged and water supplies impaired to varying extents?
3. The extent that brigades are resourced with the necessary vehicles, equipment and training, to provide effective fire-fighting under post-earthquake fire conditions?
4. The extent that the NZFS operational availability is protected from the effects of earthquake damage eg. the extent that fire station buildings and operational

infrastructure have adequate seismic capacity, and critical contents are restrained to resist shaking damage?

5. What level of response could the public expect from the NZFS to citizens requests for emergency aid following a major regional earthquake event ? Given the possibility of the impairment of the public switched telephone network due to damage and/or overloading would the NZFS modify its normal despatch procedures and methods of operation under those circumstances? What procedures are available and what knowledge does the public require in order to summon assistance from the NZFS?
6. How soon could the NZFS get back to providing a normal level of fire cover? To what extent would the constraints be a matter of water supply and / or road access disruption, and to what extent would the constraints be due to other factors, including those within the control of the NZFS?
7. Is the NZFS able to supply documentation that would provide independent verification to property owners or their insurers of whether a fire in the aftermath of an earthquake is an “earthquake fire”, as opposed to “fire as a peril” and which was caused by other means, such as fire initiation through the restoration of utility services?

15.4.3

Urban water supplies

Specific areas of interest would be:

1. What are the current earthquake design requirements for reticulated systems of water utilities, and are (or should there be) specific design codes in this area to ensure that failure is minimised?
2. Are there codes of practice in place that would provide guidance to water utilities regarding the level of spare parts and the level of specialist labour that would be required in the event of earthquake damage to reticulated water systems? Would spare parts be readily available, particularly for systems that have been in place for over ten years?
3. Are there any mutual aid arrangements in place between water utilities in New Zealand by which assistance with spare parts and specialist labour would be readily forthcoming in the event of damage to reticulated water systems in an earthquake affected region? If so, are there contracts in place that would cover this, and should there be a standard type of contract that could be used by all members of the water supply industry in New Zealand to consolidate mutual aid assistance?
4. To what extent would it be possible to reduce currently anticipated post-earthquake water systems downtime through having in New Zealand fully operative mutual aid arrangements?

15.4.4

Urban macro-scale fire protection.

The following issues were identified in Chung (1996) as offering scope for further research:

1. Construction requirements for fire resistive buildings, especially for the protection of openings such as windows and doorways.
2. Practical requirements for and means of implementation of fire resistive egress corridors for cities.

15.4.5

Development of an analytical model simulating post-earthquake fire ignition sources and the impact of control actions.

Although most, but undoubtedly not all, post-earthquake fire ignition sources and scenarios have been identified, Chung (1995) considered that they have not been adequately confirmed and quantified following past earthquakes.

It was recommended that a model should be developed to:

- assess ignitions and fire scenarios, and
- assess the impact of actions needed to reduce ignitions, and to contain or suppress post-earthquake fires.

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GLOSSARY

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1.0 Measures of earthquake magnitude and intensity

1.1

FEMA (1985) describes the magnitude of an earthquake as an indication of the amount of energy released by the earthquake. It is measured on the Richter magnitude scale (Ms) and the value for a particular earthquake is constant. In use, the Richter scale represents an increase by a factor of 31.6 for each unit increase in Richter magnitude. The magnitude (ergs) can be found from the equation:

$$\text{Log } E = 11.4 + 1.5M$$

where M is the Richter magnitude.

1.2

Scawthorn et al (1988) gave examples of Richter magnitudes as follows:

- earthquakes with magnitudes of Ms 2.0 or less are usually called microearthquakes (they are not commonly felt by people, and are generally recorded only on local seismographs)
- events with magnitudes of about 4.5 or greater are strong enough to be recorded by sensitive seismographs world-wide (there are several thousand such shocks annually)
- a Ms 5.8 earthquake would be taken as a moderate earthquake, and a strong earthquake might be rated as Ms 6.3
- great earthquakes (such as the 1964 Good Friday earthquake in Alaska) have magnitudes of 8.0 or higher. On the average one earthquake of such size occurs somewhere in the world each year.
- the largest known shocks have had magnitudes in the range Ms 8.8 - Ms 8.9.

1.3

The intensity of an earthquake is described in FEMA (1985) as being a measure of the apparent effect of the earthquake as experienced at a specific location. It is measured on the Modified Mercalli (MM) scale and the value varies with location.

Cousins et al (1990) describe the intensity of shaking as defined by the Modified Mercalli scale. It is a 12-point descriptive scale based on the observed effects of earthquake shaking on people, structures, and the ground. Representative levels for the Modified Mercalli Intensity scale are given in Table G 1.1.

1.5

A particular earthquake has only one magnitude. However, as noted in Scawthorn & Khater (1992), the same earthquake has an infinite number of intensities with each intensity being particular to a specific site. Intensities typically decrease with distance from the epicentre, and increase with “poorer” (ie. softer or weaker) soils. Thus, a very soft site at a substantial distance from an earthquake may have higher intensities than a better site (eg. on rock) closer to the earthquake.

Cousin et al noted that two types of poor soil are soft saturated soils and uncompacted sands. Soft saturated soil deposits can greatly amplify earthquake shaking, as occurred for example in Mexico City in 1985 when a low level of shaking in the rock strata underlying the city was amplified almost tenfold by resonance effects in the soils beneath the city and lead to the destruction of many relatively modern structures. Saturated uncompacted sands are prone to quicksand-like behaviour known as liquefaction that, like amplification, leads to more severe damage than on nearby competent ground. This was the predominant reason for the abnormally high levels of damage in the Marina District of San Francisco during the 1989 Loma Prieta earthquake.

2.0 Liquefaction and its effects

2.1

Liquefaction is a phenomenon involving the loss of shear strength of soil. Scawthorn and Khater (1992) noted that the shear strength loss results when shaking or vibration cause soil particles to become rearranged, consequently increasing pore water pressure.

2.2

Liquefaction has been observed in many earthquakes, usually in ground where the water table is near the surface and the soil contains soft, poorly graded granular materials (ie. loose sands). Liquefaction usually occurs in these soils during or shortly after a large earthquake.

2.3

Scawthorn and Khater described the behaviour of the liquefied soil strata effectively as that of a heavy fluid. Buried tanks may “float” to the surface, and structures founded in the liquefied strata may “sink”. Pipes passing through liquefiable materials typically sustain a relatively high number of breaks in an earthquake.

Table G 1.1: Modified Mercalli Intensity Scale (abridged)

Source: Cousins et al (1990)

Earthquake intensity (MMI)	Observed effects
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everyone runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly or badly designed structures; some chimneys broken. Noticed by persons driving motor vehicles.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor vehicles.
IX	Damage considerable even in specially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. UNDERGROUND PIPES BROKEN.
X	Some well-built bridges and wooden structures seriously damaged; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.
XI	Few (if any) masonry structures remain standing. Bridges destroyed. Broad fissures in ground. UNDERGROUND PIPE LINES COMPLETELY OUT OF SERVICE. Earth slumps and land slips in soft ground. Rails bent greatly.
XII	Damage total. Waves seen on ground surfaces. Line of sight and level distorted. Objects thrown upwards into the air.

3.0 The New Zealand Building Code

3.1

The New Zealand Building Code (NZBC) is a schedule to the The Building Regulations 1992 authorised by the The Building Act 1991. The Code sets out the mandatory provisions for meeting the purposes of the Act, and is contained in NZBC Handbook.

3.2

The Building Industry Authority (BIA) is a Crown agency established under the Act as the sole regulatory authority for building controls in New Zealand. The Territorial Authorities (TA's) are responsible within their districts for the day-to-day administration of the building control legislation.

3.3

The Code is performance based (rather than setting out prescriptive requirements) and thus, and according to the Preface to the Handbook, it says only what is to be done, not how to do it. However, the Approved Documents which are associated with the Code contain Acceptable Solutions that are for specific guidance, and are examples of materials, components and construction methods which provide a means of establishing compliance with those provisions of the NZBC to which that document refers. An owner is free to use an Alternative Solution(s) ie. any materials, components or construction methods which differ in whole or in part from those described in Approved Documents, but compliance with the relevant performance criteria of the New Zealand Building Code is mandatory, and the owner may be required to demonstrate that any such solution does in fact comply when seeking consent from the TA.

Verification of compliance may be by either of the following Verification Methods (VM's):

- calculations (using recognised analytical methods and mathematical models)
- laboratory tests (using tests on prototype components and systems)
- tests in-situ

4.0 Standard NFPA 13: 1994 - Explanation of terms and requirements

4.1

Flexible couplings

- Are required within the system at critical points to avoid stresses on the pipe.
- Defined as couplings or fittings that allow axial displacement, rotation, and at least 1° of angular movement of the pipe without inducing harm on the pipe.

4.2

Seismic separation assemblies

- Considered to be an assembly of fittings, pipe, and couplings that permits movement in all directions (ie. differential movement across the separation as well as parallel to it).
- Are intended to provide sufficient flexibility to accommodate the substantial relative motion that can be expected at building seismic separation joints (alternative is to provide each building section with its own riser, which may be more economical).

4.3

Clearance

- Necessary around sprinkler piping to prevent breakage due to building movement
- To be provided around all piping (including drains, fire department connections, and other auxiliary piping) extending through walls, floors, platforms, and foundations.
- Not required around pipes passing through successive floor joists or regularly spaced beams expected to move as a unit in the event of an earthquake, but is intended to be provided around pipes passing through beams that are considered primary structural members.
- Suitable provision to be made to prevent the passage of water smoke or fire. Annular space around piping penetrations through fire-rated assemblies to be filled with an appropriate material that is tested to ASTM E814 or similar test method, and that is flexible as installed.

4.4

Sway Bracing

- Provided to prevent excessive movement of system piping (the shifting of large pipes as a result of earthquake motion has led to pull-out of hangers and fracture of fittings).
- Must be attached directly to the building structure, and the fasteners and structural elements at the points of connection must be adequate to handle the intended loads.
- Required basic design load is an assumed horizontal force equal to 50% of the weight of the water-filled piping.
- Pipework restraint requires both lateral horizontal braces (perpendicular to the piping) and longitudinal (parallel to the piping) horizontal braces, and which are rigid and normally installed at an angle to the vertical. These are "two-way" braces - they prevent piping from moving back and forth in a single direction, whereas "four-way" bracing requires the simultaneous effect of lateral and longitudinal bracing.
- Forces applied to piping in the event of an earthquake can be vertical as well as horizontal and rigid horizontal braces installed at an angle to the horizontal will also assist the system hangers in resisting these vertical loads.
- Horizontal loads for braces may be identified through the use of either assigned pipe loads supplied in tabular form, or determined by analysis.
- A length of pipe shall not be braced to sections of the building that will move differentially without provision being made for this movement by means of flexible couplings at the point where the differential movement will be applied to the pipework.
- Sway bracing is not required for branch lines (sprinkler range pipes) as piping 2 in. diameter and smaller is considered to be capable of considerable movement without damage, although an approved means of restraint is required at certain intermediate points and at the end of each branch line to stop whipping or bouncing out of hangers. However, the exemption is not allowed where an upward or lateral movement of sprinklers would result in impact against the building structure, equipment or finish materials (damage to flush-type sprinkler heads was in evidence after the Northridge earthquake, as a consequence of considerable branch line movement and heads being pulled upward and then downward through ceilings, and where lateral movement took place simultaneously the operating mechanisms of the heads were susceptible to damage).

5.0 Standard NZS 4541: 1996 - Explanation of terms and requirements

5.1

Flexibility shall be:

- present and sufficient in pipework to prevent over-stressing of pipes, hangers and braces in an earthquake
- achieved through piping flexibility, or by the use of flexible couplings providing axial and lateral pipe connection which is equivalent to the pipe strength
- provided in risers and distribution pipes to allow for ± 80 mm of horizontal movement for every 4m of building height (to the point of interest)

- provided in the X, Y and Z axes where pipework (excluding range pipes) crosses a structural separation, to allow for relative horizontal movement of either ± 160 mm per 4 m of height of the structural separation, or the building design movement where known (Note: range pipes shall not pass through structural separations)
- provided to allow for differential movement between floors where risers pass through more than one floor and are more than 1 m from a column or structural shear wall
- provided by means of flexible couplings or adequate piping flexibility, within 600 mm to 900 mm of non-structural concrete or masonry walls to which pipework is rigidly fixed. This shall also apply to sections of pipework attached to different parts of the building, including racking systems, that may respond differently in an earthquake eg. between a wall and a roof, or between basement walls and the ground, or between a rack and a wall.

5.2

Bracing (for steel pipework) shall be:

- provided to restrain pipework under seismic load
- positioned and aligned in conjunction with flexible couplings such that no bracing is subject to seismic load from pipework outside its immediate vicinity (typical locations of pipework bracing within a building are depicted in the Standard and are intended to be used in conjunction with tabulated data, also provided, to calculate the weight of the pipework to be restrained)
- provided as lateral and longitudinal elements for the restraint of distribution piping, risers and range pipes, within the dimensional constraints specified in the Standard for positioning with respect to unrestrained ends, maximum spacing, distance from a flexible coupling and from a swing joint crossing a structural separation (the latter in the case of distribution piping)
- provided by members which when in compression are within the maximum horizontal loads as tabulated in the Standard according to brace angle
- provided snug, tight and concentric, perpendicular to the piping, with avoidance of eccentric loadings on fittings and fastenings, and remain tight under vibration
- only fixed to building elements which are capable of withstanding the force which the brace imposes on it (Standard also identifies the requirements for bracing fixings).

5.3

Clearance shall be:

- provided around all piping extending through non-structural walls, floors, platforms and foundations (Standard specifies minimum clearances according to pipe size), but the gap may be sealed with a flexible or frangible material
- exempted around all piping extending through partitions or walls of frangible materials eg. gypsum board, unless the wall is required to have a fire resistance rating (see below), or where the piping is attached rigidly to the wall and there is adequate piping flexibility on both sides of the wall to prevent damage from movement of the pipework under seismic loads
- provided around all piping extending through walls required to be fire-rated, to permit the gap to be filled with a flexible material which will preserve the fire-rating of the wall.

APPENDIX 1

Earthquakes Throughout History

Earthquakes Throughout History

References: 1 Scawthorn (1988) 2 Kenna (1975) 3 Lifelines(1991)	4 Lew (1990) 5 EERI (1984) 6 Scawthorn (1993) 7 Scawthorn (1985)	8 EERI (1985) 9 Chung (1996) 10 THE ECONOMIST (1995) 11 NZNSEE (1988)	12 Steinbrugge (1982) 13 Dowrick (1987) 14 Smith (1990) 15 Everson (1994)	16 Pender (1987)
---------------------------------------------------------------------------------	---------------------------------------------------------------------------	--------------------------------------------------------------------------------	------------------------------------------------------------------------------------	------------------

Date	Location	Severity	Fires following Earthquake	Comments
1556, January 24	Shaanxi (Shensi) Province, China	Most deadly earthquake in history; 830,000 killed.	No information.	Reference 1
1755, November 1	Lisbon, Portugal	One of the most severe of recorded earthquakes leveled Lisbon and was felt as far away as southern France and North Africa; 10,000 - 20,000 killed in Lisbon.	No information.	Reference 1
1855, -	Wairarapa, NZ	Magnitude Ms 8. No information.	No information.	Reference 3
1906, April 18 5:12am	San Francisco, California	Magnitude Ms 8.3 Extensive property damage. 700 fatalities	50 outbreaks of fire during the 3 hours following the earthquake. 3 days of conflagration. About 20,000 buildings consumed by fire. 95% of property damage due to conflagration. Eventually confined to 4 square miles by blasting.	Reference 12 Widespread damage to the underground water distribution system. Reference 2 Since this earthquake a new water distribution system has been installed, designed to cope with future earthquake fires.
1908, December 28	Messina, Sicily	Magnitude: not given City totally destroyed. About 85,000 killed.	No information.	Reference 1
1915, January 13	Avezzano, Italy	Magnitude: not given Killed about 29,980 people.	No information.	Reference 1

Date	Location	Severity	Fires following Earthquake	Comments
1920, December 16	Gansu (Kansu) Province, China	Magnitude: not given Killed about 200,000 people.	No information.	Reference 1
1923, September 1 11:58am	Tokyo / Yokohama, Japan	Magnitude Ms 8.3 Fire damage was far in excess of direct earthquake damage. Over 450,000 homes wrecked and over 100,000 people killed.	In Tokyo there were 277 reported outbreaks of fire, of which 133 spread due to high winds. Conflagration followed the earthquake, destroying many properties, and trapping thousands of people. Fire burnt an area of about 38 sq.km.	Reference 12 Reference 8 Great majority of houses were of timber of light frame construction, built along lanes so narrow that no fire engines could pass between.
1931, February 2	Hawkes Bay, NZ (Napier Earthquake)	Magnitude Ms 7.75. Towns of Napier, Hastings, Gisborne and Wairoa affected. Business areas of Napier and Hastings almost totally destroyed. 256 people killed.	Fires broke out at three points in Napier shortly after the earthquake. Ten acres of buildings were burnt out.	Reference 2 Water mains fractured. Fire engines buried in fire station.
1933, March 10 5:54pm	Long Beach, California	Magnitude Ms 6.3 120 left dead by earthquake.	At least 15 outbreaks of fire. No conflagration.	Reference 8 Destruction considerable in unreinforced masonry buildings.
1935, May 31	Quetta, India	Magnitude: not given Killed an estimated 50,000	No information.	Reference 1
1939, January 24	Chile	Magnitude: not given About 30,000 killed. Earthquake razed 50,000 square miles.	No information.	Reference 1
1939, December 27	Erzingan, Northern Turkey	Magnitude: not given City of Erzingan destroyed. about 100,000 casualties.	No information.	Reference 1

Date	Location	Severity	Fires following Earthquake	Comments
1950, August 15	Assam, India	Magnitude: not given Between 20,000 and 30,000 believed killed. Earthquake affected 30,000 square miles.	No information.	Reference 1
1952, July 21	Kern County, Central California	Magnitude Ms 7.7. 12 fatalities. About 1994 US\$280M in damage	Major oil refinery fire uncontrolled.	Reference 12 Reference 10
1957,	Daly City, San Francisco, Northern California	Magnitude Ms 5.3. No deaths. Property damage 1994 US\$5M.	No information.	Reference 10
1960, February 29	Agadir, Morocco	Magnitude Ms 5.75. Total destruction of 80 - 90% of structures in the central city area. About 12,000 people killed.	No record of fire.	Reference 2 Large number of buildings destroyed were of poor quality un-reinforced masonry in stone construction.
1962, September 1	Buyin-Zahra, Iran	Magnitude Ms 7.5. Estimated that 21,300 houses damaged beyond repair. Over 12,000 people killed.	No record of fire.	Reference 2 "Great destruction and large number of deaths due to poor construction methods." Most houses were constructed of low strength mud brick.
1963, July 26	Skopje, Yugoslavia	Magnitude Ms 6. 10% of buildings collapsed and 65% damaged beyond repair. 80% of city destroyed. Over 1000 killed and 3,350 injured.	Only two fires. "Unusual feature was the lack of fire damage."	Reference 2 The many fatalities occurred in the low cost adobe type buildings. Reference 1

Date	Location	Severity	Fires following Earthquake	Comments
1964, March 27	Anchorage, Alaska	<p>Magnitude Ms 8.4. Strongest earthquake ever to strike North America. Hit 80 miles east of Anchorage and killed 117 people. It was followed by a seismic (sea?) wave 50 feet high that travelled 8,445 miles at 450 miles per hour.</p> <p>Several buildings collapsed completely but in general damage was small considering the energy level of the earthquake.</p>	<p>No information about fire.</p> <p>No mention of fire in report although some minor outbreaks did occur.</p>	<p>Reference 1</p> <p>Reference 2 A modern city built to modern standards.</p>
1964, June 16 1:01pm	Niigata, Japan	<p>Magnitude Ms 7.5. Extensive property damage due to earthquake. Killed 24 people in Niigata and surrounding districts. Liquefaction at port facilities. Tsunami.</p>	<p>Extensive damage to oil refinery facilities due to fire which broke out in oil tanks. About 300 houses nearby destroyed by fire. Ratio of fire damage to overall shock damage was small.</p>	<p>Reference 2 Modern city area.</p>
1967, July 29	Venezuela	<p>Magnitude Ms 6.5. Four multi-storey buildings totally collapsed and several single family dwellings seriously damaged. About 250 fatalities.</p>	<p>No mention of fires.</p>	<p>Reference 2 Wide variety of construction types ranging from the low quality "Rancho" houses to modern multi-storey structures.</p>
1970, May 31	Peru	<p>Magnitude Ms 7.7. Earthquake left 50,000 dead and 17,000 missing. Severe damage over a wide area. Estimate of over 100,00 collapsed dwellings.</p>	<p>No mention of fires.</p>	<p>Reference 1 Reference 2 Fatalities and property damage occurred mainly in poorly constructed adobe dwellings. Modern city buildings did not suffer severe damage.</p>

Date	Location	Severity	Fires following Earthquake	Comments
1971, February 9	San Fernando, Los Angeles, Southern California	Magnitude Ms 6.6. 59 fatalities as a result of the earthquake. Substantial damage to old city buildings. Property damage 1994 US\$1.87B	109 fires caused by the earthquake. No conflagration occurred although there was a failure of water supplies in many areas.	Reference 2 Natural gas pipeline failures: - 52 breaks in 6 miles of 16" pipe - 9 breaks in 1 mile of 26" pipe. Replacement of 5 miles of 12" pipe. A few cases of ignition, but no explosions or other damage. Reference 10
1972, December 23	Managua, Nicaragua	Magnitude Ms 5.5 - 6.5. Managua devastated by the earthquake. 4,000 - 6,000 fatalities. 600 city blocks destroyed and 220,000 - 250,000 displaced from homes.	Fires raged through downtown blocks for 10 days. Some arson. Fire suppression equipment not operative.	Reference 1 Reference 2 Designed buildings performed well, tarquesal and unreinforced concrete and masonry severely damaged. Water, power, sewer systems and street access were disrupted.
1976, February 4	Guatemala	Magnitude: not given Over 23,000 fatalities.	No mention of fires.	Reference 1
1976, July 28	Tangshan, China	Magnitude: Ms 7.8. Earthquake devastation over 20 square mile area of the city. Estimated 242,000 killed.	No mention of fires.	Reference 1 Reference 10

Date	Location	Severity	Fires following Earthquake	Comments
1976, August 17	Mindanao, Philippines	Magnitude: not given Earthquake and tidal wave left up to 8,000 dead or missing.	No mention of fires.	Reference 1
1977, March 4	Bucharest	Magnitude: not given. Most of down-town Bucharest devastated by earthquake. 1,541 reported dead and over 11,000 injured.	No mention of fires.	Reference 1
1978, September 16	Tabas, Eastern Iran	Magnitude: not given. City destroyed by earthquake. 25,000 dead.	No mention of fires.	Reference 1
1980, November 23	Naples, Southern Italy	Magnitude: not given. 2,735 dead.	No mention of fires.	Reference 1
1982, December 13	Yemen	Magnitude: not given. 2,800 reported dead.	No mention of fires.	Reference 1
1983, May 2 4:42pm	Coalinga, San Joaquin Valley California	Magnitude Ms 6.7 No reported fatalities or injuries. Property damage 1994 US\$46M	Four structure fires.	Reference 5 Relatively small and confined emergency. Reference 10
1984, April 24 1:15pm	Morgan Hill, Northern California	Magnitude Ms 6.2 Damage from earthquake was of moderate magnitude. Felt in San Francisco Bay area & Central California Property damage 1994 US\$14M.	Three major structure fires due to heating appliance gas pipe fractures. Numerous small fires.	Reference 7 Broken water mains left some areas vulnerable in event of fire outbreak. Reference 10

Date	Location	Severity	Fires following Earthquake	Comments
1985, September 19-20 7:18am	Mexico's central and south western regions, including part of Mexico City	Magnitude Ms 8.1. MMIX in Mexico City. Vigorous after-shocks (worst was Ms 7.5 at 7:37pm 20 Oct.) Estimated 25,000 dead. Some fire deaths of trapped people.	Within 24 hours of the earthquake about 200 fires had been reported. One major fire arising from leaking gas tank, and which consumed 2 buildings. No major conflagrations	Reference 11 Organisation of fire service delayed due to collapse of HQ station. Lack of water due to broken mains and broken distribution pipes into collapsed buildings. No underground gas distribution.
1987, March 2, 1:42pm	Edgecumbe, NZ	Magnitude Ms 6.3 NZ's most damaging earthquake since the 1931 Hawkes Bay event. Caused intensity MM IX in and near Edgecumbe town. Industrial buildings sustained serious damage. About 50 houses suffered substantial structural damage, but those constructed to modern standards generally performed well.	No mention of fires.	Reference 13 Reference 14 Reference 15. Although buildings remained standing sprinkler systems within them generally didn't remain intact, and at Tasman Paper Mill sprinkler pipes fell to the floor. Reference 16. Underground services in Edgecumbe seriously disrupted, with over 400 breaks in water supply.
1987, October 1, 7:42am	Whittier Narrows, Los Angeles Southern California	Magnitude Ms 5.9. 7 fatalities and 100 injured. Damage to over 200 buildings Property losses 1994 US\$467M	By noon 75 gas fires, 38 structure fires.	Reference 10

Date	Location	Severity	Fires following Earthquake	Comments
1989, October 17 5:04pm	Loma Prieta, Northern California	Magnitude Ms 7.1. 65 fatalities (including 2 fire fatalities). 3757 injuries. Major damage to highway systems in San Francisco Bay area. Property damage 1994 US\$7.1B	Losses due to fire were minor compared to structural damage. Serious fire spread halted by a combination of precautionary measures, favourable weather conditions and good fortune.	Reference 4 Public fire protection systems were severely interrupted. Underground water distribution systems showed extensive failure. Reference 10
1993, July 12 10:17pm	Hokkaido Nansei-oki earthquake, Northern Japan	Magnitude Ms 7.8 246 people dead or missing. 190 houses and buildings consumed by fire over 11 hour period. Tsunami damage over a wide area. Damage from liquefaction at port facilities. Overall cost of damage in excess of US \$1B .	Town of Aonae destroyed by conflagration following earthquake and tsunami. Building- to-building fire spread accelerated by externally stored propane and kerosene tanks used for cooking and heating.	Reference 6 Earthquake occurred off-shore of the Island of Hokkaido. Followed by a large tsunami (wave height 30.5m) which devastated the town of Aonae on shoreline of Island of Okushiri, and areas along coast of Hokkaido.

Date	Location	Severity	Fires following Earthquake	Comments
1994, January 17 4:31am	Northridge, San Fernando Valley Southern California	Magnitude Ms 6.7. 58 fatalities (none from fire). 1500 serious injuries. US most costly natural disaster. Close to epicentre peak lateral accel. 1.8g, peak vertical accel. 1.2g. Property losses 1994 US\$20B	30 - 50 significant fires initially following earthquake. Total of about 110 fires before noon, but <u>no conflagration</u> . Principal cause was gas leaks from natural gas pipelines and appliances. Most fires occurred in San Fernando Valley. Building-to-building fire spread only in mobile home parks. Restoration of gas and power in the days following caused significant number fires.	Reference 5. Disruption to water supplies. Damage to fire protection systems within buildings (some sprinkler systems). Loss of life and property from fire would have been far greater had it not been a federal holiday (traffic light), and for favourable weather conditions (high RH. and light winds) limiting fire spread. Reference 10
1995, January 17 5:46am	Kobe City Hanshin District, Japan (but also affected neighbouring Osaka and Kyoto Cities).	Magnitude Ms 6.9 Shaking intensity exceeded MMVIII. 6,000 fatalities (over 500 deaths were caused by fires) and 30,000 injured. 100,000 buildings were destroyed either by the earthquake or by fires that followed. Close to epicentre peak lateral accel. >0.8g, peak vertical accel. approx 0.5g. Property losses 1994 US\$110B	205 fires occurred in Kobe & neighbouring cities on the first day (89 started within 14 minutes of the main shock). Total of 240 fires by midnight four days later (this included 11 very large fires having burned areas > 10,000 sq.m). Worst affected area was Kobe's Nagata Ward where approx. 160 acres and more than 69,000 buildings were consumed. Rapid re-instatement of utility gas and electricity supplies was significant cause of fresh ignitions.	Reference 9. Modern urban cities, but most two storey tile rooved wooden structures collapsed & fuelled fire spread. Fire dept. helpless to prevent fire spread due to lack of fire-fighting water from fire hydrants & to closeness of buildings & impaired access. Control of fire spread in Osaka more successful due to alternative water. Reference 10

APPENDIX 2

Review of Selected Earthquakes Events

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1. 1906 San Francisco, Northern California Earthquake

The earthquake	This earthquake is known as San Francisco earthquake of 1906. The event is also referred to as the "1906 fire".
When Magnitude Intensity	It occurred at 5:12am on April 18, 1906, and as reported by Scawthorn (1986) the main shock had a magnitude of 8.3 on the Richter Scale, and a maximum intensity of MM IX in San Francisco.
Location of epicentre Area affected. Earthquake expectancy. Demographic detail. Geotechnical perspective.	<p>This earthquake originated in the St Andreas fault.</p> <p>These issues were not defined in the references available.</p>
Human toll	According to EERI (1985) there were about 700 fatalities (about 500 in San Francisco, and about 100 near San Jose at the collapse at Agnews Asylum).
Economic loss	Scawthorn et al (1988) reported the damage loss due to the fires that began as a result of the earthquake was 1992 \$US7 billion, and was the largest single loss due to an earthquake in the history of the United States.
Infra-structure damage Damage to structures	<p>This issue was not defined in the references available.</p> <p>EERI (1985) reported that the damage due to shaking was relatively light, amounting to about 20% of the total damage in the city of San Francisco. Santa Rosa sustained greater shaking damage in its business district, due to poor quality masonry construction, but also suffered major damage due to fire.</p>
Fire following earthquake	<p>According to Scawthorn et al (1988) fire razed more than 10 sq. km of the city, destroying at least 28,000 buildings.</p> <p>Scawthorn (1985) noted that 50 outbreaks of fire were reported within the hour following the earthquake.</p> <p>According to EERI (1985) these 50 fires grew quickly to conflagration proportions because of lack of water.</p> <p>Steinbrugge (1982) reported that the conflagration lasted three days and caused substantially more damage than the earthquake. He noted that the original outbreaks of fire were in a quarter characterised by soft ground, which coincided with the predominance of building damage and in breaks in water, gas and sewer pipes.</p> <p>Scawthorn et al (1988) described the post-earthquake fire problem as typically complex and involving many diverse elements, as follows:</p> <ol style="list-style-type: none">1. The <u>earthquake</u>, which causes structural and non-structural damage to buildings. <p>Structural damage results in loss of integrity of many of the fire safety elements of buildings on which occupants normally rely eg.</p> <ul style="list-style-type: none">• failure of fire-resistant construction such as firewalls, fire doors and fire-resistant wall facings such as stucco

- loss of serviceability of active fire protection, such as automatic fire alarm systems and sprinkler systems.

Non-structural (infra-structure) damage to urban lifelines, eg.

- water supplies
- gas supplies
- transportation systems
- communications networks (delays in reporting fires to the fire service allowed them to grow rapidly, escalating the demands on fire response)
- electrical generation and distribution.

2. Fires, which break out initially and then spread before fire-fighting teams arrive, depending on
 - building density, and the nature of the fire load
 - climatic conditions (wind and humidity).
3. Fire-fighting teams, which have to respond to multi-skill demands (eg. fight fires, attend other emergencies such as chemical spills, building collapses), and could have impairment of water supplies, communications, road access, which results in
 - not all fires being responded to
 - some fires spreading.
4. Result: some small fires, or conflagration?

Fire causes

Steinbrugge (1982) reported some fire causes:

- fracturing of internal electrical wiring as the result of structural damage to buildings (the electrical service current was not shut off for some minutes after the initial shock)
- some crosses of 550 volt tram wires with other wires, and the consequent sparking and arcing of working electrical appliances and circuits in buildings collapse of buildings containing fires in open fire places, lit kerosene lamps and gas lights in dwellings and businesses, boiler fires in factories.

Fire spread mechanisms

According to Steinbrugge the major elements necessary for conflagration were present after the earthquake:

- fire load per unit area was high
- a degree of impairment of fire response facilities (eg. water supplies were disrupted, and the fire department was over-extended to cope with the magnitude of the fire challenge)
- adversity of climatic conditions (eg. the absence of rain, but persistent wind changes played a major role).

Steinbrugge noted that San Francisco was 90% timber frame buildings, a larger proportion than that in any other city of its size in the country. Frame buildings of a considerable height, 4 or 5 stories, were common. The dwelling district was almost entirely frame, large sections being not scattered, as was usual in frame dwelling districts, but in compact blocks. The frame feature greatly facilitated the rapid spread of fire.

The wind conditions were also noted:

- during the early hours of the day of the earthquake the wind was generally light and from the west. It carried the fire into a territory of low, strung-out blocks bounded by the Bay. Some water could be obtained and some fires were brought under control.
- By a succession of three further wind changes the conflagration systematically maximised its devastation over the following three days.

Damage to fire safety systems	<p>According to Kenna (1985), water supplies to sprinkler systems were disrupted by distribution pipe damage.</p> <p>There was no information in the references available as to how other fire safety systems performed during the post-earthquake fires.</p>
Effect of earthquake on water supplies	<p>EERI (1985) reported that the fires quickly grew to conflagration proportions due to complete water supply failure. The lack of water was due to the failure of the three water transmission lines feeding the city from the Peninsula, and the widespread damage to the distribution system in the city itself. The water transmission lines failed where they crossed marshy ground.</p> <p>According to Steinbrugge (1982) over 23,200 separate service pipes were torn off by the burning and falling buildings during the conflagration and left running wide open during the entire conflagration discharging uselessly into the accumulated debris. This left but little pressure in the main pipes in the unburnt district and for the fire department along the burning margin of the same.</p> <p>Steinbrugge noted that water was always available in the Western Addition residential section of San Francisco during the entire conflagration.</p>
Response of the fire department	<p>According to Steinbrugge the lack of regular means of communications and the absence of water in the burning district seriously disrupted the fire department response.</p> <p>The fire alarm headquarters were wrecked by the earthquake and could not receive alarms, and the telephone system also broke down over a considerable area and there were many unsuccessful attempts to send in alarms.</p> <p>No fire department engines were seriously disabled by the earthquake and all went into service.</p>
Lessons to be learned	<p>According to Scawthorn et al (1988) the San Francisco earthquake of 1906 was the largest single loss in the history of the United States, but it was the result of fire and not earthquake. It was predicted that depending on wind and other factors the potential for disasters of this magnitude remain with us today.</p>

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2. The Japan (Tokyo / Yokohama) Earthquake, 1923.

The earthquake	Although this event is referred to variously as the Japan 1923 earthquake, the 1923 Tokyo / Yokohama earthquake, the Tokyo 1923 catastrophe etc. its formal name is The Kanto Earthquake of 1923.
When Magnitude Intensity	It occurred at 11:58am on September 1, 1923, and as reported by Kenna (1975) the main shock had a magnitude of 8.3 on the Richter Scale.
Area affected	According to Kenna the effects of this earthquake were widely felt through the Province of Kwanto but were borne mainly by the population centres Tokyo and Yokohama.
Location of epicentre. Earthquake expectancy. Geotechnical perspective.	These issues were not reported in the references available.
Human toll	<p>Steinbrugge (1982) reported that over 100,000 lives were lost in Tokyo and environs.</p> <p>According to Kenna many thousands were trapped by the fire. People could not leave the burning city because of burnt out bridges, or because bridges were blocked by opposing traffic. Forty thousand people sheltering on the one large open piece of ground adjoining the Military Clothing Depot perished due to suffocation when a sudden wind change forced the fire on them.</p>
Economic loss	Not reported in the references available.
Infra-structure damage	<p>According to EERI (1985) public works damage was extensive and included:</p> <ul style="list-style-type: none">• Port and Harbours - collapse of quay walls, such as Yokohama where a 2,000m long 7m high concrete block structure was completely demolished• Roads - embankment settlement, pavement cracking, and bridge collapse (1,156 bridges severely damaged or collapsed)• Waterworks - contamination of supplies, as well as structural damage to dams and widespread pipe breakage.
Damage to structures	<p>Kenna reported that the earthquake wrecked over 450,000 light framed houses. Many people were trapped in buildings in which the roofs collapsed preventing escapes before the fire reached them.</p> <p>According to Steinbrugge the customary Japanese tile roof added mass to the light wood frame, and therefore dwelling collapse or serious damage was relatively common.</p> <p>EERI (1985) reported that well-engineered buildings suffered relatively light shaking damage.</p>
Fire following earthquake	<p>According to Kenna post-earthquake fire caused more extensive property damage than that caused by the earthquake.</p> <p>Steinbrugge also reported that fire damage was far in excess of direct earthquake damage, and that post-earthquake fires were uncontrolled and burnt large areas for days. There were 277 reported outbreaks of fire in Tokyo, and 133 of these fires spread. About 40% of the area of Tokyo City was destroyed by fire, which burned for nearly 40 hours, and 90% of Yokohama was destroyed by earthquake and fire.</p>

Kenna stated the reporting incidence of fires occurring immediately after the earthquake as:

- 53 initial outbreaks reported within a few minutes of the earthquake
- a total of 134 initial outbreaks
- over 100 were general, and 30 were chemical fires.

In Tokyo fires burned 38 km² and destroyed 450,000 houses.

Fire causes

Kenna noted that this earthquake occurred while the midday meals were being prepared and therefore there would have been a large number of heating units and stoves in operation. The weather conditions would also have influenced the chances of initial outbreaks occurring.

According to Steinbrugge meteorological records in Tokyo gave wind velocity at the time of the earthquake as 27.5 mph.

Kenna classified the ways in which primary fire outbreaks occurred:

1. Direct contact between combustibles and the fire or hot materials as the result of -
 - displacement of the heat source
 - displaced materials falling onto the heat source
 - the container of the heat source fracturing.
2. Over-turning of heat sources (stoves, kerosene lamps, heaters, cookers, braziers).
3. Electrical short-circuits as the result of -
 - movement of defective wiring
 - displacement of supports
 - contact between circuits normally separated.
4. Burst fuel tanks.
5. Rupture of gas and oil supply lines.
6. Chemical fires -
 - liquids and vapours from broken containers
 - disturbance to the regulation of industrial processes.
7. Fires intentionally lit.
8. Freak fires.

According to Kenna the risk of primary outbreaks may be reduced, but it is not possible to eliminate all such outbreaks. Incipient outbreaks do not represent a serious hazard provided they can be contained or extinguished before spread of fire occurs.

Oppenheim (1984) reported that the causes of most of the general fires were kitchen ranges, clay charcoal cooking stoves and braziers burning wood and charcoal as fuels. The chemical fires occurred at pharmaceutical and medical colleges, universities, technical high schools, apothecaries, dental clinics and soap factories.

Fire spread mechanisms

Oppenheim reported that Japanese urban areas have closely spaced dwellings of highly combustible construction. He reported some aspects concerning fire spread (which he defined as the growth of a fire in an urban area following a specific ignition):

1. Fire spread results from house-to-house ignition which is generally caused by one of three mechanisms:
 - radiation
 - firebrands, or
 - flame impingement.
2. Fire spread is essentially a result of the "fuel layout" of the area:
 - the buildings
 - their materials
 - their spacing.

3. Fire spread is further influenced by:
 - temperature
 - humidity
 - wind conditions.
4. Fire spread demonstrates the potential, or propensity, of an urban area to burn ie. its conflagration potential.

Oppenheim considered that conflagration potential is the single most important factor governing fire loss following a damaging earthquake. In areas with high conflagration potential very high fire losses can be expected, and it is not likely that engineering improvements for fire suppression would reduce those losses. He noted, however, that those losses could be reduced in the long term:

- by planning (zoning) actions, or
- by the development of strategies (such as fire breaks) to control the almost certain conflagration.

Steinbrugge also reported that the spread of fires and their continued burning were functions of the large amount of wooden construction, but considered other factors, as follows:

- inability to fight fires due to broken water mains and
- extremely adverse climatic conditions.

Steinbrugge noted the wind conditions following the earthquake from meteorological records in Tokyo:

- at the time of the earthquake (12 noon) the velocity was given as 27.5 mph, from a southerly direction
- at 6:00pm the wind changed its direction, westerly, 27.5mph
- at 8:00pm it changed to north-westerly, 23.3mph
- between 9:00pm and midnight velocity increased, to peak at 48.8mph
- midnight to 4:00am next day, less than 30mph.

Mehaffy & Richardson (1994) also reported that, among other factors, the close proximity of heavily damaged buildings constructed with wood structural members and wood exterior components fostered rapid fire spread once fire commenced.

Damage to fire safety systems

Kenna noted that the late detection of initial fire outbreaks was an important factor favouring the spread of fire, as:

- the earliest detection of incipient outbreaks is of utmost importance to ensure that minimum manpower and equipment is needed to extinguish the fire
- building occupants should in most cases be able to extinguish such outbreaks, and eliminate further outbreaks (eg. by turning off gas, electricity and kerosene burning heaters)
- when fire is not controllable by building occupants, delay is often due to failure of the communication system to the brigade.

In many later earthquake events followed by fires, communications permitting early reporting has not always been possible mainly because of damage to fire department central control buildings, to the telephone services, and to emergency power supplies, but the extent that any of these factors applied during the Japan earthquake 1923 was not reported in the references available.

Effect of earthquake on water supplies

Kenna also noted that the failure of water supply systems was a most important factor contributing to the spread of fire after this earthquake. Complete water supply failure occurred.

Steinbrugge also reported that the network of underground water pipes traversing the city was demolished and broken in numerous places, and water was seen gushing out. Also many water hydrants were destroyed by the flames so that water leaked away everywhere. At the reservoirs of the city water works, numerous cracks occurred in the filter and cleaning beds, but no further damage occurred, except that the filtering capacity was affected to some extent.

**Response of the
fire department**

Kenna noted other factors which contributed to the spread of fire and which concerned fire brigade response:

- the fire brigades' difficulties with access to the fires - access to fires was blocked by collapsed buildings and bridges, and fissured and slumped roads
- fire stations were also damaged, preventing the use of some fire vehicles and equipment
- poor town planning: many of the houses were so close together that brigade vehicles could not pass between them.

Steinbrugge reported that with the loss of the water system, fire-fighters attempted to get supplies of water from moats and other reservoirs at distant places. With these limited supplies they fought the fires for 46 hours continuously, and succeeded in subduing outbreaks at 23 places.

Fatalities and injuries were reported as 22 firemen killed (mostly burnt to death) and over 100 were injured.

**Lessons to be
learned**

Some of the lessons to be learned from the Japan 1923 earthquake are:

1. According to Oppenheim, "conflagration potential" (ie. the potential or propensity of an urban area to burn) is the single most important factor governing fire loss following a damaging earthquake.
2. Kenna reported that the risk of primary outbreaks of fire may be reduced (eg. by introducing engineered improvements for fire protection), but it is not possible to eliminate all such outbreaks. However, incipient outbreaks do not represent a serious hazard provided they can be contained or extinguished before spread of fire occurs.
3. Steinbrugge noted that towns which have closely spaced buildings (of high combustibility), narrow streets and few green belts represent high fire risks, and if water supplies fail, there is little that can be done other than by demolishing some buildings to provide fire breaks. Oppenheim suggested that in the long term fire losses could be reduced by planning (zoning) actions, or by the development of strategies (such as permanent fire breaks) to control almost certain conflagration.

3. 1931 Hawkes Bay, NZ Earthquake

The earthquake	This event is known as the Hawkes Bay earthquake of 1931, and also the Napier earthquake.
When Magnitude Intensity	It occurred at 10:48am on Tuesday, February 3, 1931, and according to Kenna (1975) the main shock lasted for at least one minute and had a maximum intensity of 7.75 on the Richter Scale. It was followed by many severe aftershocks during the weeks following the main event.
Location of epicentre Area affected	According to Daily Telegraph (1981) this was in the Mohaka area. The towns of Gisborne, Napier, Hastings, Waipukurau, and many country districts, were devastated by this event
Earthquake expectancy. Demographic detail. Geotechnical perspective	Information on these issues was not provided in the references available. Campbell (1975) reported that some 7,000 acres of the Napier lagoon area rose by about 5 feet, and this later provided a massive new area of safe land for housing and industry.
Human toll	According to Daily Telegraph (1981) in excess of 150 people were killed and 300 were injured. Kenna (1975) reported that over 60% lost their lives on the footpaths where they were overwhelmed by falling masonry, or were trapped while attempting to escape from collapsing buildings. Of the remainder, the greater proportion would have been those trapped within buildings in Napier such as at the Nurses' Home (8 fatalities), Park Island Home (10 fatalities), Technical College (10 fatalities), Roach's Drapery Store (17 fatalities) and the Greenmeadows Seminary (9 fatalities).
Economic loss	This was not given in any of the references available.
Infra-structure damage	Campbell (1975) reported that in Napier the electricity supply was cut off by the shaking of the earthquake, but power was supplied to the main feeders by the evening of the following day. Gas supplies were cut off, but restoration details were not given. Almost all water pipelines were damaged by shaking and ground movement, and the fire brigade quickly ran out of water for fire-fighting. In Hastings the water supply also failed due to the collapse of the Havelock bridge carrying the water mains to the town.
Damage to structures	Daily Telegraph (1981) reported that all brick buildings were destroyed. Reinforced concrete and wood escaped more lightly, though the damage even then was enormous.
Fire following earthquake	According to the Daily Telegraph (1981) there were three initial, or primary, outbreaks of fire that occurred almost immediately after the earthquake, and these were in chemists' shops. The fire spread to a fourth building, the Masonic Hotel, from one of these shop fires. It was fully expected that the fires would be confined to these four buildings because of the calm conditions, but just before noon a brisk easterly blew up and before many minutes the fire was raging throughout the whole of the central business district.

The Daily Telegraph reported that already the town had been razed by the earthquake, but the fire, fanned by still freshening winds made terrific in-roads among the ruins of the demolished buildings. At least one hundred fires were blazing at once late on Tuesday night. It swept across the town until its further progress was stopped only by extensive open spaces.

Kenna (1975) reported that the Napier post-earthquake fire was a major conflagration which burnt out 10 acres of city buildings. It showed that should fire once get out of control little can be done without easy access and adequate water supply; and the blasting of a line of buildings to isolate the fire provided the only means available to prevent spreading, where extensive open spaces were not available in some directions.

The Daily Telegraph reported that Hastings fared only a little less disastrously than Napier. Fire originated in the ruins of the Grand Hotel and carried by a light breeze it swept a city block. Fire raged, and a dislocated water supply left a fire brigade helpless to fight the flames.

Fire causes

The Daily Telegraph reported the verdict of Mr J.S.Barton after the inquest ordered by him in connection with the post-earthquake fires. It was found that the fires which originated in three chemists' shops and were caused by conditions following the earthquake comprising:

- damaged buildings
- scattered stock-in-trade
- broken light, heat and power reticulation.

The evidence was of the violent emptying of shelves and the breaking of their containers, and the spreading and mixing of their contents on the floors of the shops, dispensaries and store rooms. Bottles containing inflammable and highly volatile liquids were broken, and had released fluids and vapours which were readily ignitable by the Bunsen lamps used in the chemists' shops.

Fire spread mechanisms

A result of the Enquiry as reported by The Daily Telegraph in regard to the fire spread was that conditions were favourable to the spread of fire:

- the day of the earthquake was hot and fine, and followed a dry spell of weather
- at the time of the outbreak of fire in the three chemists' shops (at about 10:50am) the wind was westerly, or off-shore, but within half to one hour of the earthquake it changed to an easterly or south-easterly wind which drove the fire from two chemists' shops (one fire had been suppressed by the owner) into adjoining buildings, and then through the central business district of the town.

A recommendation was made at the Enquiry by the Fire Superintendent for wire glass windows and fire-proof doors to be used in city business areas.

Fire spread was by flame contact from wind-borne fire, and by lofted fire brands.

Damage to fire safety systems

There were no reports found on the existence, or effectiveness of fire safety systems.

Effect of earthquake on water supplies

Kenna (1975) reported that complete water supply failure occurred after the Napier earthquake, and this contributed a most important factor to the spread of fire. He noted that cast iron mains were badly fractured at junctions, and at joints the lead packings were disturbed allowing extensive leakage. Additionally, a hill top reservoir was badly fractured and a high pressure water tower overturned.

According to Daily Telegraph (1981) the water pressure was comparatively weak from the beginning, and gradually grew less 'til it failed completely within an hour of the earthquake.

Campbell (1975) reported that almost all water pipelines had been damaged by the earthquake and that the fire brigade did not have enough water to save many buildings, but obtained a supply from a pumping station and a salt water sump, which was enough to stop the fire spreading along Hastings, Munroe and Carlyle Streets.

The Daily Telegraph reported that Hastings' water supply also failed, due to the collapse of the Havelock Bridge and with it the mains water supply to the City.

**Response of the
fire department**

According to The Daily Telegraph the Napier Central Fire Station was destroyed by earthquake shaking and fire engines were buried. Faced with an inadequate water supply the fire brigade attempted to pull down buildings, and dynamite buildings, so as to keep the fire within bounds. By Wednesday morning they had won, although the fires smoldered in the ruins for several days. Only a few buildings survived the holocaust which burnt out 10 acres of city buildings.

Campbell (1975) also reported that the fire brigade used dynamite to isolate blazing buildings.

**Lessons to be
learned**

According to Kenna (1975) the Napier earthquake showed that outbreaks of fire shortly following upon earthquakes should be expected. He noted that:

- the complete water supply failure after the Napier earthquake contributed a most important factor to the spread of fire
- it showed that should fire once get out of control little can be done without easy access and adequate water supply
- town water supply systems should incorporate the highest safeguards against breakage and water loss under earthquake conditions
- the use of sea water or of other natural water supplies by fire brigades should be an anticipated emergency measure pending the restoration of normal town supplies after a severe earthquake.

Kenna (1975) also provided further more general recommendations:

- building occupants should be trained to deal with post-earthquake fires while in the incipient stage, using any hand extinguishing or portable hose equipment
- occupants should turn off gas, electricity and fuel-burning heaters, and ensure all smoke- and fire-stop doors are closed
- occupants of multi-storey buildings should then immediately descend to safer lower storey escape levels
- emergency water supply measures should provide for portable pumps in conjunction with temporary storage tanks, to be available to relay emergency water supplies from harbour, lake or river sources to fire risk areas.

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4. 1933 Long Beach, California Earthquake

The earthquake	This event is known as the Long Beach Earthquake.
When Magnitude Intensity	It occurred at 5:54pm on Friday March 10, 1933, and according to EERI (1985) the main shock had a magnitude of 6.3 on the Richter Scale, and a maximum intensity of MM IX.
Location of epicentre	The epicentre was centred of-shore on the Newport-Inglewood fault zone, about 25km from Long Beach.
Area affected. Earthquake expectancy. Demographic detail. Geotechnical perspective	These issues were not defined in the references available.
Human toll	According to EERI (1985) this earthquake resulted in 120 fatalities, but there were no details provided on the number of people injured or left homeless.
Economic loss	EERI (1985) reported that the damage from this earthquake amounted to about \$US50 million.
Infra-structure damage	Details not provided in the references available.
Damage to structures	<p>EERI (1985) reported that destruction was considerable in unreinforced masonry buildings which was the predominant structural type for schools, and only the time of the event (5:54pm) prevented major casualties among school children.</p> <p>According to Kenna (1975) the unsuitability of unreinforced masonry type buildings for schools led to the passage of the Field Act by the State of California, marking a new point in earthquake hazards mitigation by requiring aseismic design for all new school construction.</p>
Fire following earthquake	According to EERI (1985) there were about 15 outbreaks of fire, but none resulted in conflagration. Steinbrugge (1982) reported that no fires occurred in sprinklered risks.
Fire causes. Fire spread mechanisms	Details not provided in the references available.
Damage to fire safety systems	<p>Seismic cut-off valves</p> <p>Kenna (1975) reported that the Long Beach earthquake occurred while many evening meals were being prepared. It had been estimated that 35,000 gas flames were burning but that good engineering on the part of the Gas Department lessened the chance of conflagration through the operation of cut-offs at supply points.</p> <p>According to Kenna the primary fire hazard can be reduced by the rapid shutting off of gas and electricity supplies either by a pre-arranged disaster procedure or by auto cut-offs actuated by seismic shock.</p> <p>Sprinkler systems</p> <p>According to Steinbrugge (1982) this was the first major instance of reported performance of sprinkler systems during an earthquake, and it brought about earthquake bracing standards for tanks and piping.</p>

Steinbrugge quoted details from the study of sprinkler system performance by the Board of Fire Underwriters of the Pacific:

- probably 500 sprinklered properties were in the earthquake effected area
- at least 150 risks were subjected to severe strain by reason of location in the immediate area of severe structural damage.

Of the (approximately) 150 sprinkler protected properties in the area of severe damage:

1. 20% was sprinkler protection that had been completely shut down due to broken mains risers, principal water supply shut off or destroyed (about 50% due to townmain breakage in the streets), or due to extensive structural damage
2. 40% was sprinkler protection that had been partially impaired through one water supply being out of service, or through partial shut-down of systems on account of broken small overhead mains etc.
3. 40% was sprinkler protection that had remained operational or was at worst shut down for a few hours for inspection and minor repairs after the earthquake.

The sprinkler protection as described in 1. was to a significant extent (given as 60%) restored to partial or approximately normal operating condition within 72 hours after the earthquake occurred.

By the above described damage levels it was considered a fair assumption by Steinbrugge that 80% of the sprinkler equipments would have been able to cope with normal fire occurring in the buildings under protection, and within 72 hours about 90% of all risks were returned to approximately normal operating condition by means of temporary repairs.

According to Steinbrugge the need for automatic sprinkler systems to remain functional after an earthquake is vital since public fire protection systems (fire departments) may be impaired (by loss of townmain water supplies, impediments to road access etc.). Should the city water supply fail, on-site water supply becomes vital.

Effect of earthquake on water supplies

Steinbrugge reported that underground main breakage occurred, particularly in filled ground on Long Beach water front. No further details were provided.

Response of the fire department.

Details not provided in the references available.

Lessons to be learned

Steinbrugge considered that the analysis of sprinkler system performance following the Long Beach earthquake identified, in rational terms:

1. The vulnerability of sprinkler piping and tanks to:
 - the direct effects of building damage from earthquake shaking
 - the inertia forces on sprinkler system components (subsequently addressed through the introduction of earthquake bracing standards).
2. The vital importance of an on-site water supply to ensure the hydraulic capacity of the sprinkler system in event of loss of townmain water supplies.

Kenna considered that the value of seismic cut-off valves for the rapid shutting-off of gas and electricity supplies (manually or automatically) in reducing the primary fire hazard (and risk of conflagration) was demonstrated in the aftermath of this earthquake by the absence of gas-fuelled conflagration.

5. 1964 Niigata, Japan Earthquake

The earthquake	This event is known as the Niigata earthquake.
When	It occurred at 1:00pm on 16 June, 1964.
Magnitude	According to Kawasumi (1964) the main shock had a magnitude of 7.5 on the Richter Scale, but no information was provided as to the maximum intensity of this earthquake. However, it was reported to have caused a tsunami wave which flooded some parts of the City of Niigata, and carried buoyant oil slicks from ruptured oil bulk storage tanks and pipelines, through major industrial areas and some neighbouring residential areas. The ignition of these spillages and the consequent rapid fire spread, compounded the already heavy damage suffered by structures due to earthquake shaking and ground displacement.
Intensity	
Location of epicentre.	Details not provided in the references available.
Area affected.	
Earthquake expectancy.	
Demographic detail	Over 300,000 people in the City of Niigata affected by the earthquake.
Geotechnical perspective	<p>According to EERI (1985) this earthquake is familiar to most researchers due to its classic liquefaction and the resultant damage that occurred to public works. Works damaged included ports and harbours, roads and railways, and waterworks (refer to Infra-structure damage).</p> <p>Kawasumi (1964) reported that sub-soil conditions greatly influenced damage levels. Particularly heavy shaking damage was caused to structures on weak formations of thick sand layers.</p>
Human toll	According to Kawasumi there were 26 fatalities, and 227 injured as a result of this earthquake.
Economic loss	Kawasumi reported a total loss figure of 4.6 billion Yen from this earthquake.
Infra-structure damage	<p>EERI (1985) reported that shaking damage was relatively light, and most other damage was to public works due to liquefaction and/or tsunami (2m high at Niigata). Public works damage included:</p> <ul style="list-style-type: none">• Ports and Harbours. Failure of piers and quaywalls, but the extent of the damage depended on their age and design levels.• Roads and Railways. Cracking of pavements, settlement of embankments, failure of bridges (combined with surface flooding, road damage is reported to have significantly delayed the access of fire department vehicles to fires).• Waterworks. Breakage of underground water pipes leading to the failure water supplies.
Damage to structures	<p>According to Kawasumi the extent of earthquake damage, and the damage from post-earthquake fires, was considerable:</p> <ul style="list-style-type: none">• 2,125 buildings were totally destroyed (333 by fire)• 6,238 buildings were partially destroyed (one by fire).
Fire following earthquake	<p>Kawasumi reported that there were at least nine post-earthquake fire origins:</p> <ul style="list-style-type: none">• four fires were extinguished immediately, before spreading beyond the room of fire origin• five fires were of major proportions, one causing a conflagration in a residential area.

The reported details of the fire incidents (which were extinguished immediately) were as follows:

- Municipal High School Chemistry Lab fire. Stored containers of chemicals, which were shaken from shelves, were broken and ignition occurred when their contents mixed. Occupants could not extinguish the fire using first aid fire-fighting appliances, but fire department extinguished it by spreading sand over the burning chemicals.
- Mitsubishi Metal Mining Company laboratory fire. Circumstances as for High School fire, except that staff were able to extinguish the fire using a fire hose water jet.
- Confectionery factory fire. An unsecured LPG container was shaken from a shelf and the rubber supply line to an oven was severed. The leaking case ignited and some wall linings were burnt before the fire department could extinguish the fire.
- Restaurant fire. Earthquake shaking caused a cooking oil spill from a deep-frying pan and was ignited by a heated brick oven. This fire was extinguished by the owner using a foam extinguisher.

The reported details of the major fire incidents were as follows:

- Showa Oil Company oil storage tanks fire. This fire involved five oil tanks and spread into a conflagration which burned more than 300 homes. On the third day following the earthquake fire-fighters arrived from the Tokyo Fire Department to assist the local fire-fighters. Consequently, the fire was contained and burnt itself out.
- Niigata Oil Refinery oil storage tank fire. Tank # 1103 on this site contained 27 million litres of crude oil. The cause of ignition was thought to have been a spark from the collision of metallic parts (floating roof and the brim of the tank) as the result of earthquake shaking and the sloshing of the tank contents. Both tank contents and spilled oil was burning, and an adjacent residential area was eventually destroyed by the spreading fire. The fire was contained but was not subdued until 1700 hours on 1 July (14.5 days after the earthquake), by which time it had burnt itself out.
- Narusawa Mineral Oil Company fire. Fire began in an oil distillation tower, spread to oil spilled across the site by earthquake shaking, and razed all combustible buildings and facilities on the plant premises.
- Nitto Textile Mill fire. Fuel leaking from an underground crude oil pipe adjacent to this site ignited. Fire spread to oil spillages on the surface of a flooded area around the mill. All the mill's warehouses were razed. The fire department was delayed by damaged and flooded roads and arrived as the fire was spreading to engulf neighbouring houses. Its further progress was then halted by the fire-fighter's actions.
- Fujishima Saw Mill fire. Earthquake shaking caused ignition in the plant bath-house. Access to the site for the fire department was impossible due to severe flooding, road damage and liquefaction over parts of the terrain. Likewise on site fire-fighting was reported almost impossible due to the site being flooded by surging tsunami waves. Fire spread to all combustible buildings of the factory and which burnt to flood water level.

Fire causes

The causes of the post-earthquake fires were not all reported by Kawasumi (1964), but those described included:

- sparking from the collision of metallic parts due to the slopping of contents, as the result of earthquake shaking of oil storage tank # 1103
- exothermic chemical reactions from spilled chemicals in storage, which caused the ignition of adjacent combustibles
- LPG leakage ignited by a working oven
- cooking oil spill ignited by a hot surface.

From Kawasumi's account of the fires, the retained and spilled contents of the storage tanks provided an enormous fire load in that part of Niigata City, and which was supplemented by many combustible industrial and residential

structures, also containing high fire loads.

Fire spread mechanisms

From Kawasumi's report of the conflagrations which developed in several residential areas it is apparent that fire spread was promoted by:

- the burning oil slick on the tsunami-driven flood waters which engulfed some residences adjacent to the tank farms in the river estuary area
- the typically high-density housing and narrow streets of the residential areas, and by the combustibility of the materials of their construction.

No information was provided as to the climatic conditions prevailing during the time of the post-earthquake fires. However, the writer suggests that fire spread through an urban area, promoted to some extent by a burning oil slick on tsunami-driven flood waters, is an unusual element in fire spread by conflagration.

Kawasumi's report suggested that had it not been for the flood, fire would have spread to a much greater extent, and destroyed wider areas.

Damage to fire safety systems

No information was provided on these issues in Hirose's report.

Effect of earthquake on water supplies.

EERI (1985) reported that underground pipes including water lines were broken. However, no further information was provided as to the effect water line damage had on water supplies and fire-fighting efforts.

Response of the fire department

Kawasumi's report suggested that the Niigata Fire Department was overwhelmed by difficult access conditions, and which delayed fire-fighting response to the oil tank fires in the flooded areas by about 4 hours. These fires quickly proved to be beyond the resources and ability of the local fire department to control, and were left to burn 34 hours until reinforcements and specialist assistance from the Tokyo Fire Department arrived and took over fire-fighting using multiple deliveries of foam. Fire spread was controlled but the contents of tanks were allowed to burn out. Tank #1103 burnt for a further 11 days before its fire was finally subdued.

Lessons to be learned

Kawasumi report referred to several lessons from this earthquake:

- the need for adequate allowance for earthquake shaking in the warehousing and storage of hazardous chemicals, regardless of quantities, and for arrangements to be in place for the containment of fire to within storage areas should chemicals drop and ignitions occur
- the extreme difficulty in fighting oil tank and oil spill fires. These require special fire-fighting responses in terms of skills, equipment and extinguishants, and a highly co-ordinated fire-ground management.

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6. 1971 San Fernando Valley, Los Angeles, California Earthquake

The earthquake	The event is known as the 1971 San Fernando, California earthquake.
When Magnitude Intensity	It occurred at 6:00am on 9 February, 1971. According to CDGS (1975) the main shock had a magnitude of 6.5 on the Richter Scale, but 35 aftershocks with a Richter magnitude of 4.0 or more were recorded within the first 7 minutes following the main shock. Aftershocks continued to be felt for many months. The duration of the strong motion was about 12 seconds. The maximum intensity of the earthquake was felt in the range MM VIII - X in the San Fernando and Sylmar regions. Ground accelerations were measured in the range 0.2g - 0.5g in the areas of strong to very strong shaking.
Location of epicentre	Steinbrugge (1982) reported the epicentre to be located in the San Gabriel Mountains about 16 km north of the City of San Fernando at a focal depth of about 8 km.
Area affected	According to CDGS (1975) the earthquake brought havoc and devastation to communities in the north-western San Fernando Valley, and severe damage to the suburb of Sylmar in Los Angeles City. Damage was noticeable more than 50 km from the epicentre.
Earthquake expectancy	CDGS (1975) reported that although the San Fernando earthquake was unpredictable in its location and timing, an earthquake of at least the magnitude of that event occurs somewhere in this region on the average of about once every 4 years, and in that sense the San Fernando earthquake was no great surprise.
Demographic detail	According to CDGS (1975) the population within the areas of strong to very strong ground shaking was about 2.5 million. This included the population of the heavily hit San Fernando Valley area (1.2 million).
Geotechnical perspective	Steinbrugge (1982) reported that the earthquake damage was due partly to the surface effects of faulting, partly to ground shaking, and partly to a combination of both.
Human toll	<p>CDGS (1975) reported that 64 fatalities were attributable to the earthquake, and 2,540 people received injuries. The collapse of a building at the Veterans' Administration Hospital in the foothills of the San Fernando Valley claimed 47 lives, and 3 lives were lost due to a building collapse at the Olive View Hospital. Three fatalities resulted from the collapse of a freeway bridge.</p> <p>It was estimated that 90% of the people within the area of the earthquake were in their homes at the time of the main shock. It was considered that the number of persons killed or injured was very much lower than it would have been had the earthquake struck later in the morning when people would have been in more hazardous settings (eg. in the shopping centres and on the highways that sustained serious damage).</p>
Economic loss	<p>According to Kenna (1975) the estimated total monetary loss from the earthquake amounted to \$511 million. Most of this occurred in the Sylmar area.</p> <p>EERI (Nov.1986) reported this earthquake showed that property losses due to non-structural damage may considerably exceed losses due to structural damage in moderate earthquakes.</p>
Infra-structure damage	<p>Power</p> <p>Power supplies were interrupted for varying periods after the earthquake. According to EERI (Nov.1986) this was due in part to the severe damage to inadequately anchored switch-yard plant and equipment, resulting from the</p>

earthquake shaking. Within the main area of devastation power was unavailable for periods of up to one week. In most other parts it was restored within two days.

Gas service

According to Steinbrugge (1982) there was major damage to gas transmission systems and to gas distribution pipe lines mainly caused by permanent ground movement. Gas mains were cracked or broken and gas leakage caused some fires. Gas supplies were restored to most customers in 5 days and to the remainder in 11 days.

Telephone service

CDGS (1975) reported that parts of the telephone system in the Los Angeles area were seriously disrupted due to physical damage, power supply outages and overloading of telephone circuits. The disruptions made contacting the fire department difficult. The worst damage was to poorly anchored telephone switching equipment at the Sylmar CO. Damage to modern telephone buildings and other communications facilities and equipment was minor. Complete restoration of service was achieved in 21 days.

Damage to structures

According to CDGS (1975) the earthquake damaged approximately 20,000 houses and destroyed, or nearly destroyed, 830 of them. There were many outbreaks of fire. The destruction of buildings, and the consequent tragic loss of life (total of 54 people died due to building collapse) dramatically revealed the unsafe construction of some residential buildings. The deaths nearly all took place in buildings that were not built to earthquake-resistant codes. In the City of San Fernando approximately 30% of the residential structures sustained appreciable damage. In Los Angeles city, severe damage occurred in the suburb of Sylmar.

Steel frame and reinforced-concrete high rise buildings generally performed well.

Damage was sustained by some sections of the Los Angeles highway system, but no reports were found of this impeding fire department progress to fire emergencies.

Fire following earthquake

Steinbrugge (1982) reported that conflagrations did not follow the earthquake although 116 fires were reported throughout the metro Los Angeles area. Of these, 109 were in the San Fernando Valley and vicinity.

CDGS (1975) and Kenna (1975) also noted that over 100 outbreaks of fire were reported but no serious spread of fire occurred, although water supplies failed in many areas. CDGS (1975) provided a breakdown of fire incidents:

- Los Angeles Fire Department responded to 128 fires of which two were major
- Los Angeles County Fire Department responded to 32 fire calls
- City of San Fernando Fire Department had only three fire calls directly attributable to the earthquake, and of these only one was a structural fire, which was minor.

EERI (Nov. 1986) reported that following the earthquake, flames were produced in the gas mains in the streets of San Fernando, and fires in buildings resulted from ruptured service lines.

According to CDGS (1975) only two or three fires occurred in the streets at broken gas lines. One of these burned for 4 hours before the fire was extinguished. It also noted that fire damage to structures due to gas leakage was minor.

Fire causes

CDGS (1975) reported fire causes as:

- electrically sourced ignitions due to severed electrical wiring (was the cause of some house fires)
- ignition of leaking gas from ruptured gas lines (caused fires in some mobile homes after they had been shaken off their jacks), and ignition of leaking gas from some buried gas distribution mains in the Sylmar - San Fernando areas (broken in the streets due to permanent ground movement and probably ignited by a passing vehicle).

It was also suggested that the danger of fire would have been much greater had the earthquake occurred during periods of heavy traffic.

According to Steinbrugge (1982) the Los Angeles building department reported "innumerable" water heaters dislodged or turned over in that city. However, the author noted that only one incident was known to have been the cause of a fire.

Fire spread mechanisms

CDGS (1975) and Kenna (1975) noted that no serious spread of fire occurred.

Steinbrugge (1982) reported that conflagration did not follow this earthquake, as the elements necessary for conflagration were not present, or not significant to this event, namely:

- fire load per unit area (ie. density of combustible material), and areal extent, were low
- degree of impairment of fire response facilities (ie. the extent that fire-fighting resources were committed, that access to fire grounds was impeded by debris or traffic congestion, that water supply from street hydrants was restricted)
- adversity of climatic conditions.

Damage to fire safety systems

According to Steinbrugge (1982) this earthquake provided a significant example of sprinkler system performance:

- generally speaking, if a sprinklered building fared well, so did the sprinkler system
- out of 973 sprinklered buildings detailed in Pacific Fire Rating Bureau files and located in the effected areas, available reporting and news sources indicated 68 buildings were considered possibly to have suffered damage, and these were assessed (the actual sprinkler system damage levels are tabulated below)
- of the 100 sprinklered installations requiring repairs by private contractors, the majority concerned minor needs only (eg. slight leaks, broken hangers or sway braces etc.).

Damage	Buildings Damaged		Sprinkler			
	No.	%	System No.	damage %	Leakage No.	loss %
None	6	9	30	44	40	59
Slight	25	37	16	24	12	18
Moderate	13	19	9	13	7	10
Severe	24	35	13	19	9	13
Totals	68	100	68	100	68	100

**Table: Damage to Sprinkler Systems,
1971 San Fernando, California, Earthquake**
Reference: Steinbrugge (1982)

**Effect of
earthquake on
water supplies**

According to CDGS (1975) water supplies failed in many areas. The water system for the City of San Fernando was devastated:

- wells were ruptured
- reservoirs were cracked
- distribution system was so fractured that it had to be almost entirely rebuilt.

Kenna (1975) also reported damage occurred to all sections of the supply system, and that many pump stations not structurally damaged were rendered inoperative due to failure of power supplies to the electric motor driven pumps.

According to CDGS (1975) the breaks in the water lines throughout the disaster area caused an acute shortage of water for basic needs, and where fire hydrants were unserviceable water was drafted from swimming pools for fire-fighting. More than 400,000 gallons of water were delivered by tank to various locations during the period that water was in short supply.

CDGS (1975) reported that considering the extent of the damage sustained by the water system, restoration was surprisingly quick, with restoration to less seriously effected parts of the damage area in 4 - 5 days and to all areas within 4 weeks.

**Response of the
fire department**

From the breakdown of fire incidents provided by CDGS (1975) the deduced total of post-earthquake fire calls throughout the earthquake effected area was 163. The Los Angeles Fire Department alone reported 436 post-earthquake incidents (128 fire calls) as compared to a February daily average of 73 incidents.

According to CDGS (1975) the disruption to the telephone service in parts of the Los Angeles area seriously impeded the public in seeking fire department assistance.

However, no information was available in the references to hand that explained how or whether the fire department coped with the alert and dispatch situations, nor how the fire response facilities handled the workload. That fire spread did not occur was probably an indication that the fire-fighting resources were adequate and that any additional problems with water supplies etc did not significantly impede the fire department's efforts.

**Lessons to be
learned**

According to Kenna (1975) the risk of fire hazard occurring appears to be lessening where modern seismic building design standards are observed. In the San Fernando earthquake this resulted in at least the following:

- less major earthquake damage to buildings
- less consequential street blockages to delay fire-brigade access
- improved fire-fighting facilities, and
- more fire-resistant methods of construction.

Steinbrugge (1982) has suggested that a building's structural integrity imposes a limit to the extent that the building's sprinkler system will provide an earthquake-resistant response when exposed to shaking. He noted that, however excellent might be the earthquake bracing for the sprinkler system, it cannot be better than allowed by the structural integrity of the building. This implicitly means that water damage from broken sprinkler systems remains a constant threat in certain building types. Therefore, there is the potential for significant earthquake sprinkler leakage damage, even if the building complex is designed with damage control in mind.

Steinbrugge also identified the fundamental requirement for integrity of the sprinkler system water supplies. To remain fully functional after an earthquake in which outside water supplies might be cut off, there must be on-site water storage with earthquake braced standby power (for pumping).

7. 1972 Managau, Nicaragua Earthquakes

The earthquake	The event is known as the 1972 Managua earthquakes.
When	They occurred at 12:30am, 1:18am and 1:20am on 23 December, 1972.
Magnitude	Foreshocks began at 10:00pm the previous evening
Intensity	<p>EERI (Nov. 1973) reported that the shocks in the city of Managua were of the order of 5.5 to 6.5 on the Richter Scale. The duration of shaking of the main shock at 12:30am was 5 - 10 seconds The greatest zone of damage was in the older downtown area of Managua which was exposed to earthquake intensities of up to MM IX. The area of MMI VIII - IX shaking was in excess of 65 km², and of MMI VII - VIII shaking about 100 km².</p> <p>Damage was due to strong shaking, faulting, and fire in the downtown area. Moderate to extensive building damage, including collapses, extended virtually everywhere in the vicinity of Managua.</p> <p>The maximum acceleration had been estimated as 0.5g in downtown Managua.</p>
Location of epicentre	According to EERI (May 1973) the epicentre of the main shock was in an area approximately coinciding with downtown Managua and at a depth of 2 - 8 km. The shallow focus of these earthquakes intensified damaged.
Area affected	According to EERI (May 1973) cities located 15 - 20 km from Managua were not damaged although the earthquakes were strongly felt.
Earthquake expectancy	<p>EERI (Nov.1973) reported that the area has been seismically active during the past 100 years and this earthquake was one of several destructive shocks experienced in that time. Many failures of the earlier, and disastrous, 1931 earthquake were faithfully reproduced in 1972, and given as:</p> <ul style="list-style-type: none">• no significant emergency planning• no seismic-resistant construction• no redundancy and decentralization of emergency services. <p>Despite the small tremous a few hours before the tragedy, this earthquake caught the people and Government officials unawares, and the only emergency plan draft available was burned in the ruins.</p>
Demographic detail	According to EERI (Nov.1973) the estimated population of the affected area was 420,000.
Geotechnical perspective	EERI (May 1973) reported that four roughly parallel lines of surface faulting devastated underground services. The foundation conditions did not lead to any particular problems related to serious slides or local amplification of ground motion.
Human toll	EERI (Nov.1973) reported the official Government estimates of 4,000 - 6,000 dead, 20,000 injured and 220,000 - 250,000 displaced. Many deaths occurred to sleeping occupants in homes of taquezal (adobe and timber beam) construction.
Economic loss	According to EERI (Nov 1973) the cost of property damage was estimated to be \$US700 million which may be compared with the value of the Gross Domestic Product of the country in 1967.
Infra-structure damage	<p>Power</p> <p>According to EERI (May 1973) although no damage was reported to the hydro-electric plants to the north of the city, and overall damage to the main diesel-electric and steam-electric generating plant in Managua was slight, severe</p>

damage occurred to the electrical distribution system in downtown Managua. Poles, wires and transformers were badly damaged by fire and debris from damaged and collapsed buildings.

EERI (Nov.1973) reported that power ceased automatically throughout all areas of the city and most of the Pacific Region.

Telecommunications

According to EERI (May 1973) local telephone communications was not functioning due to equipment damage in the old central telephone exchange building in downtown Managua and in several other smaller exchanges outside of town. Therefore fires could not be reported by telephone. However, long distance telephone, microwave and satellite systems were operating.

Damage to structures

EERI (Nov.1973) reported that the earthquake destroyed an area of 13 km² of the City of Managua. Another 14km² of the city was seriously damaged. Seismic considerations were not mandatory, and this factor contributed to the loss of such key structures as fire and police stations, hospitals, Government offices, and communications centres.

Most modern high-rise structures not situated on faults sustained the shock without collapse and often without significant structural damage. However, the architectural and non-structural components of these newer buildings were often damaged severely, and mechanical systems were generally inoperative after the earthquake.

Non-structural damage, including damage to elevators and the blocking of stairways, would have complicated evacuation of buildings and increased the death toll if the earthquake had occurred during working hours.

About 53,000 housing units were lost or seriously damaged and at least eleven major industrial facilities suffered nearly total or very serious damage to their structural and equipment systems. However, numerous industrial facilities survived the damage due to the proper application of earthquake engineering principles, although in many cases with only minimal earthquake-resistant design.

Unanchored equipment slid and collided, and ruptured electrical connections and piping.

Fire following earthquake

According to EERI (Nov.1973) fires broke out in four or five places within a very short time after the earthquake. Fire department resources were quickly overwhelmed as many pieces of their equipment were buried in fallen buildings. The fires developed to a conflagration and raged virtually uncontrolled for three days.

On December 27 a firebreak was begun to prevent their further spread. This action, together with continued fire-fighting, was successful.

According to Kenna (1975) fire raged uncontrolled through many downtown blocks in Managua for a week after the earthquake.

Steinbrigg (1982) reported from personal observations that fires were still burning 10 days after the earthquake.

According to EERI (Nov.1973), by December 30 (7 days after the earthquake) 162 blocks had been gutted (an area of approximately 0.8km²).

Steinbrigg (1982) and Kenna (1975) both reported the mysterious outbreak of fires, 2 days after the earthquake. Apparently many properties insured for fire

were not covered for earthquake damage. There was also the persistent rumour that many of the fires were intentionally started as a mechanism for diverting attention from organised crime.

According to EERI (Nov.1973) the Managua post-earthquake fires gave a severe fire test to some buildings. Edificio Carlos, the 6-storey reinforced concrete moment-resisting frame building that housed the First National City Bank was one of a number of buildings that was burned out completely. Everything combustible in the building was totally consumed. The report considered it remarkable how little structural damage resulted. Some of the plaster spalled and some of the hollow clay tiles in the tile-formed concrete floor system popped due to the intense heat of the fire below. According to this report, the building gave a dramatic display of the ability of the plaster reinforced concrete structure to resist damage by fire.

Fire causes

With the exception of a reference to arson as a possible fire cause about two days after the earthquake, the causes of the fires immediately following the main shock were not reported in the references available. However, EERI (Nov.1973) reported that power ceased automatically throughout all areas of the city after the earthquake, and since it was off in the fire-affected area for many days following then it is deduced that electrical ignition is ruled out as an ignition source.

Fire spread mechanisms

EERI (Nov.1973) referred to the Managua post-earthquake fires as mass fires. Steinbrigg (1982) and Kenna (1975) both referred to them as conflagrations. No reports were found which identified the rate of fire spread, or the prevailing climatic conditions.

However, Kenna referred to some of the circumstances in the Managua downtown area that supported conflagration conditions:

- high fire load per unit area and the closeness of the buildings
- a degree of impairment of fire response facilities (difficult access for fire-fighters and their equipment due to the narrow streets, and additionally, due to street blockages from building collapse as the result of earthquake shaking; also a lack of fire-fighting water).

According to Kenna (1975) the hazard of fire spread in high rise buildings where several hundred occupants could be trapped by fire in the higher floor levels was very much a possibility following the Managua earthquake in two modern high rise buildings of reinforced concrete construction, had it not been for the time of day that the earthquake struck.

Had fire occurred immediately following the earthquake, and had the shock occurred during working hours, life loss would have been substantial because of debris-littered stairwells, jammed doors and inoperative elevators. Fires on any floor would have spread quickly from storey to storey (where combustible material existed) through shattered fire resistive enclosures around stairs and elevator shaft walls. Fire suppression and rescue efforts would have been very difficult.

Damage to fire safety systems

This issue was not reported in the references available.

Effect of earthquake on water supplies

EERI (Nov. 1973) reported that the underground piping of water distribution systems were badly damaged particularly in poor ground areas and across earthquake faulting. The distribution system consisted of over 600 km of piping from 1" up to 30" using materials which included ductile iron, cast iron, galvanised iron, asbestos cement and PVC. There were many breaks in the street water mains, water leaks within residences and many breaks in the storage tanks.

The absence of water at hydrants severely hampered fire-fighting operations, and was given as one of the reasons why fires were able to rage uncontrolled through many downtown blocks in Managua for over a week after the shock. This earthquake emphasised the sensitivity of cities to the survival of their water supplies (as well as power communications and other lifelines). Within a day water supplies were re-established to the western sectors of the city, but in many other areas water tank trucks were used for weeks to supply water at public supply points.

Response of the fire department

According to Steinbrigge (1982) the Fire Department's post-earthquake fire response capabilities were greatly diminished by the earthquake damage. He reported that:

- fire stations collapsed on the trucks and other equipment
- narrow streets were blocked with debris, impeding the use of vehicles
- water was generally not available at fire hydrants due to badly damaged water distribution systems.

EERI (Nov.1973) reported the damage to the Fire Department buildings. Headquarters were accommodated in a 3-storey reinforced concrete building. There were two other stations, one in downtown Managua on the north side of the city near Lake Managua, and another in the densely populated area on the west side of the city. All stations suffered very heavy earthquake damage, and most of the equipment was trapped under the rubbish.

According to EERI (May 1973) the west side fire station was a two storey concrete structure with fire-fighting equipment at ground level and firemen's quarters on the first floor. The first storey collapsed, 8 pieces of equipment were lost and two firemen were killed.

EERI (Nov.1973) noted that a report had been circulated to the effect that the crew on duty at Headquarters on the evening of December 22 had moved the fire trucks outside upon feeling a foreshock (in accordance with standing instructions). The crew which came on duty at midnight returned the apparatus into the building, just in time for the earthquake.

The fires that broke out in four or five locations within a very short time after the earthquake according to EERI (Nov.1973) were fought by the fire department with what equipment was available. Pumps were also set up to draw water from Lake Managua.

Five days after the main shock, and with the fires still raging, firebreaks were begun (provided by the Public Works department bulldozers) to prevent their further spread. This action, together with continued fire-fighting, was successful.

Lessons to be learned

Kenna (1975) suggested that the conflagration which developed from the post-earthquake fires of this event, as for a number of earthquakes previously, reinforced the factors which aid the conflagration condition, which include:

- the failure of the water supply system
- lack of fire-fighting resources
- impairment of fire response facilities due to difficulties in accessing the fire sites.

EERI (Nov.1973) stressed the importance of the impact of building damage on fire safety in multi-storey buildings. After this earthquake many stairways were partially or wholly blocked due to jammed doors and debris. In multi-storey buildings stairways are required for exiting occupants, and in addition to stairways elevators may be required (firemen's lifts) for fire-ground access and equipment transport for fire control purposes. When stairs are blocked by

debris and smoke, and elevators are out of operation, critical emergency egress and fire fighting response problems are created. This problem is compounded at night due to electrical power failures and the lack of emergency lighting.

Elevators deserve special mention: it was reported that after this event none of the numerous elevators inspected were operable due to damage to counterweights, guides, machinery and controls.

It suggested that the presence of buildings without any intentional lateral strength in a city with a severe earthquake history re-emphasised the need to pass and enforce laws to prevent the construction of such buildings in seismic regions.

According to EERI (Nov.1973) some plaster reinforced concrete structures eg. Edificio Carlos Building gave dramatic displays of their ability to resist damage by fire.

EERI (Nov.1973) stressed that current plans for all elements of the fire service are essential, and should make provision for:

1. A definite line of succession.
2. Protection of personnel and equipment from the intermediate effects of the disaster.
3. Use of personnel and equipment on a perimeter basis to fight mass fire.
4. Alternate sources of water.
5. Use of rotary-wing reconnaissance aircraft, forest fire-fighting aircraft, heavy stream appliances, heavy off-road equipment and such special equipment as self-contained breathing apparatus and powered cutting tools.
6. Acquisition of mobile communications equipment and facilities, and training in its use.

EERI (May1973) reported that the main utilities were out of service when they were most needed, and stressed that water, electrical and communications systems should be designed with redundancy in mind. Several sources or centres and alternate routes are desirable. The ability to shut off services to damaged areas and re-route around them is essential. Portable units (eg, fire-fighting water pumps) will increase the redundancy.

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8. 1984 Morgan Hill, Northern California Earthquake

The earthquake	The event is also known as the Halls Valley earthquake.
When	It occurred at 1:15pm on 24 April, 1984.
Magnitude	
Intensity	<p>EARTHQUAKE SPECTRA (May 1985) reported that the earthquake's mean local magnitude was 6.2 on the Richter scale, and it produced 5 - 10 seconds of strong shaking. The maximum intensity was MM VIII at Morgan Hill, in the suburb of Jackson Oaks.</p> <p>Morgan Hill and the immediate area south and west experienced peak accelerations of 0.40g to 0.50g (0.50g at Jacksons Oaks, a modern residential subdivision, and at United Technologies Chemical Systems Division, a 5,200 acre industrial complex where missile fuel is tested and produced). This level of seismic motion is supported by the observed damage to various buildings and by the sliding of unanchored equipment at various sites.</p> <p>A series of aftershocks occurred for a further 8 months, the largest being 4.5 on the Richter scale 9 days after the mainshock.</p>
Location of epicentre	According to EARTHQUAKE SPECTRA (May 1985) the epicentre was located in Hall's Valley, 40 miles south of San Francisco in the lightly populated vicinity of Morgan Hill.
Area affected	Scawthorn (1985) reported that shaking was felt not only in the Morgan Hill area but also over a large part of the San Francisco Bay area (40 miles from the epicentre) and in the heavily populated San Jose area (about 10 miles north of the epicentre).
Earthquake expectancy	EARTHQUAKE SPECTRA (May 1985) suggested a recurrence period of 75 years for this earthquake.
Demographic detail	According to Scawthorn (1985) a large percentage of the San Francisco Bay area's 5.0 million inhabitants were jolted by this earthquake. The San Jose area with population 730,000 and the city of Morgan Hill with about 18,000, were more seriously threatened.
Geotechnical perspective	Hoose (1984) reported that the earthquake generated a few minor liquefaction effects, and site soil amplification increased damage.
Human toll	There were no fatalities or significant injuries due to this earthquake reported in the references studied.
Economic loss	<p>THE ECONOMIST (1995) reported property damage at 1994 \$14 M .</p> <p>Hoose (1984) reported that there was \$7.5 M damage primarily in the community of Morgan Hill, and an estimated \$1.5 M damage at the United Technologies Chemical Systems Division Facility, neglecting business interruption.</p> <p>According to Scawthorn (1985) reported losses and less publicised damage to sensitive industrial facilities may reach \$20 M.</p>
Infra-structure damage	<p>Power</p> <p>EARTHQUAKE SPECTRA (May 1985) reported power loss in most of southern Santa Clara Valley for up to 5 hours following the earthquake due to significant damage to equipment at two substations, and some damage to feeders in the distribution system.</p>

Communications

According to Scawthorn (1985) there was no significant damage to communications systems, although there was a significant downgrade in the quality of service of the telephone system due to overload. The telephone system was the only means of reporting fires in San Jose. This resulted in delayed reports of structural fires to fire departments.

Natural gas system

EARTHQUAKE SPECTRA (May 1985) reported that there was no damage to the utilities part of the system, although there were numerous leaks beyond the service connections to homes in high damage areas, and numerous gas leaks on premises due to toppled water heaters. However, only one large fire was fuelled by a gas leak.

Damage to structures

According to EARTHQUAKE SPECTRA (May 1985) this earthquake was of only moderate size within the context of California earthquakes. Seismic damage to well-engineered systems and structures was minimal to non-existent. Even though some system structures did show signs of distress, and recorded peak ground accelerations were high, structures in general were not seriously damaged.

Most residential structures suffered little or no damage. In the majority of homes suffering damage, the damage was non-structural in nature. This interior damage was by far the major loss to residences in the earthquake, and was the largest single source of dollar loss.

Damage to a sprinkler system at United Technologies Chemical Systems Division Facility was reported:

- a few pipe hangers failed and these caused the piping to break at couplings
- falling HVAC ducting impacted and damaged fire sprinkler piping.

Fire following earthquake

According to EARTHQUAKE SPECTRA (May 1985) post-earthquake fire was a primary cause of damage in the cities of Morgan Hill and San Jose. A fire in a shopping centre in San Jose was the largest single loss in the earthquake, approximately \$1M.

Scawthorn (1985) reported (and confirmed by EARTHQUAKE SPECTRA (May 1985), that of the 79 reported earthquake related incidents in the six hours following the earthquake six were structure fires (two in Morgan Hill and four in San Jose). These involved four residences and two commercial buildings. The largest, in a shopping centre in San Jose, was reported about 15 minutes after the earthquake by a citizen driving to the nearest fire station. However, flashover occurred shortly after the fire department arrived, and fire spread through the attic area of this single storey wood framed, wood shake roofed structure to the other two businesses in the building.

According to this report it took 60 minutes to contain the fire to one building, using about 50,000 gallons of water. Despite a wind speed of 16mph, fire did not propagate to a neighbouring building of similar construction only six feet away.

Fire causes

EARTHQUAKE SPECTRA (May 1985) reported that the causes of two major structural fires in the Morgan Hill and San Jose areas were broken natural gas pipes to heating elements in gas appliances (to a water heater in a Morgan Hill mobile home, and to a gas heater in the shopping centre fire in San Jose).

Scawthorn (1985) reported several residential fires occurred due to chimney and gas heater flue damage, and one in which the gas service had been restored one hour prior to the fire.

According to EARTHQUAKE SPECTRA (May 1985) three fires were caused by the arcs from electrical short circuits, and overheating:

- in an attic fire in a commercial laundry, where electrical shorting in steel conduit caused a hot spot and the ignition of cotton lint in contact with it
- from a snapped power line falling onto a dwelling roof, arcing through the metallic roof covering and igniting structural members and contents. This caused a total loss due to the delay in reporting the fire (with the telephone service overloaded a citizen had to drive to the nearest fire station to get assistance).
- a flood light fell onto the roof of a residence at the time of the earthquake. It was turned on automatically by a timer device and the light overheated and ignited the roof covering (this fire was quickly reported and extinguished).

Three grass fires were caused by “wires down” arcing to ground.

Scawthorn (1985) reported that caution exercised by the citizens was effective in preventing ignition of leaking gas in the Jackson Oaks area where the major damage in Morgan Hill occurred. Residents had turned off about 30% of their gas service and the Fire department completed the cut-off of all gas and electricity.

**Fire spread
mechanisms**

The only report of fire spread between structures was from EARTHQUAKE SPECTRA (May 1985) which described fire spread due to flying brands, and the ignition of the wood shake roof of a dwelling approximately one block downwind from the San Jose shopping centre fire (peak wind speed at the time had been recorded as about 16mph). The fire was extinguished and total damage was confined to approximately a 3m x 3m area of the roof.

**Damage to fire
safety systems**

None of the reports available provided information on this issue, except that damage to fire sprinkler systems (as reported previously in Damage to Structures) may have compromised their performance if they had been activated in a fire incident.

**Effect of
earthquake on
water supplies**

According to EARTHQUAKE SPECTRA (May 1985) large water losses occurred in Morgan Hill due to breaks in two transit water lines, and numerous water service connection failures in the high damage area.

Scawthorn (1985) reported that due to water main breakage about 500 homes were without water for several days so that outbreak of fire was a serious concern.

**Response of the
fire department**

According to Scawthorn (1985) in an attempt to counter the absence of fire-fighting water in the area the Morgan Hill Fire Department stationed a water tank truck at the scene, sufficient to control a small fire.

EARTHQUAKE SPECTRA (May 1985) reported that the incidents relating to the Morgan Hill earthquake made the greatest demands on the local fire departments ever experienced. The multiple non-fire specific incidents which fire departments were required to respond to (such as gas leak investigations, structural damage checks, downed power lines and medical aid) placed additional heavy demand on limited resources.

This report predicted that, although able to cope at all times during the Morgan Hill earthquake, fire department capacity would be exceeded in attempting to respond to the aftermath of an earthquake of only moderately higher intensity.

Scawthorn (1985) reported fire department post-earthquake incident load, and compared it with an average workday load:

- in Morgan Hill there were approximately 35 incidents in the nine hours

following the earthquake, as compared with 1.9 incidents per day

- in San Jose there were approximately 62 incidents within five hours (average of 12 per hour), as compared with about 3.5 to 4.5 incidents per hour on an average day.

According to EARTHQUAKE SPECTRA (May 1985) San Jose Fire Department statistics indicated that 55 minutes after the earthquake 52 of the 72 fire units were committed to the post-earthquake emergencies. The San Jose fire district area is 206 square miles, and has 680 personnel in 28 fire stations and four district headquarters.

Scawthorn (1985) reported that the City of Morgan Hill fire department has 14 paid-on-call and 30 volunteer fire-fighters, and is equipped with four fire units. There is also a Californian Division of Forestry station on the outskirts of Morgan Hill with three engines equipped for brush fires.

According to EARTHQUAKE SPECTRA (May 1985) the San Jose Fire Department dispatching centre's computer temporarily "crashed" due to a power outage.

Lessons to be learned

Telephone reporting of incidents

According to Scawthorn (1985) Emergency Services should expect less than ordinary telephone response following a major earthquake, and should be prepared with alternative communications methods to optimally allocate resources.

After the Morgan Hill earthquake communications were an essential but vulnerable link in the fire-fighting effort. Overload of telephone systems can generally be expected to occur following an earthquake due to increase in telephone use and the built-in protection of the equipment causing a slow-down in dial-tone being received (with delays as long as 30 seconds these could be perceived as a phone outage).

The telephone system was the sole means of reporting fires in San Jose, but to counter the perceived phone outage after the earthquake citizens had to resort to driving to the fire stations to report incidents, and in some instances this caused critical delays to the arrival of emergency assistance.

Emergency Services Despatching Centre Reliability

According to EARTHQUAKE SPECTRA (May 1985) emergency services operations should not rely on computers without dependable back-up power, and despatching centre operations should be regularly exercised with "computers down".

Decreasing fire-fighters' workload

In major emergencies the fire-fighters limited resources are overburdened by incident load which is not specifically fire-related. According to Scawthorn (1985) some of these tasks should be co-ordinated with and assumed by utility companies, roading departments, structural engineers, medical services etc.

Restoration of utilities

Restoration of utilities (gas and electricity) can result in fires hours or days after the initial disaster. According to EARTHQUAKE SPECTRA (May 1985) strategies for service restoration should include:

- restoring service only after individuals are present in every structure, with public officials authorised to enter structures where owners are absent, in order to check for fire, or gas leaks
- fire units should stand by in the area at the time of utility restoration.

9. 1985 Mexico City Earthquake

The earthquake	This event is known as the Michoacan - Guerrero Mexican earthquake.
When	It occurred at 7:18am on Thursday 19 September, 1985.
Magnitude	
Intensity	<p>NZNSSEE (1988) reported its magnitude as Richter 8.1, and produced 60 seconds duration of severe shaking. In the worst affected areas of Mexico City it produced damaging intensities of MM IX that affected especially those structures that responded to low frequencies.</p> <p>According to Cassaro & Romera (1985) ground accelerations ranged from 0.05g to 0.2g in a period range of 1.5 to 3 seconds. The total duration of sustained shaking continued for about 3 minutes. A large aftershock occurred at 7:38pm on Friday September 20, with Richter magnitude 7.5, and perceptible shocks continued for a further two more weeks.</p> <p>According to EARTHQUAKE SPECTRA (August 1988) the 19 September earthquake was the most damaging to have occurred in North America, and probably the most severe one since the middle of last century. Before 1985, the worst experience in Mexico City was that of 1957 with an earthquake intensity of Richter 7.7, at an epicentral distance of 260 km.</p>
Location of epicentre	<p>According to EARTHQUAKE SPECTRA (August 1988), the epicentre was approximately 10 km off the Pacific Coast of Mexico, north of Zihuatanejo, and about 400 km east of Mexico City.</p> <p>NZNSSEE (1988) reported that within the earthquake's epicentral region buildings were damaged selectively according to their construction types and vibration characteristics, and intensities varied over the range MM VII to MM IX.</p>
Area affected	According to NZNSSEE (1988) the earthquake's destructive effects were unusually widely distributed. Within Mexico City damage to buildings was confined to an area of approximately 65 sq. km, with a zone of approximately 25 sq. km where collapse or severe damage to buildings occurred.
Earthquake expectancy	Cassaro & Romera (1985) reported that seismic activity in this region causes Mexico to experience about five times as many earthquakes as California.
Demographic detail	According to NZNSSEE (1988) Mexico City is the world's most populous metropolis with a 1985 population of 17 million, covering an area in excess of 1,000 sq.km and containing in excess of 1.5 million structures.
Geotechnical perspective	EARTHQUAKE SPECTRA (August 1988) reported that the extensive damage caused in Mexico City by this earthquake called to attention the influence of local soil conditions on the resonant amplification characteristics of earthquake ground motions (this influence had been taken into account in subsequent building codes).
Human toll	According to EARTHQUAKE SPECTRA (August 1988) this earthquake caused some 10,000 fatalities, about 30,000 were injured, and in excess of 50,000 were left homeless.
Economic loss	Social and economic disruption was immeasurable. Material losses amounted to about US\$4 billion.

Infra-structure damage**Electricity supply**

NZNSEE (1988) reported that immediately after the earthquake 40% of the 3.2 million customers in Mexico City had lost their electricity supply. The main problem was with failures in the distribution system (collapse of power poles, damage to overhead power lines and underground cables, and to transformers) rather than with electricity generation. Most of the electricity supply for Mexico City comes from outside the Valley of Mexico and there were no long-term problems with generation, or damage to the powerhouses or switchyards in the earthquakes.

Most of the services were restored rapidly, and only 1% of the customers were affected long-term.

Gas

According to NZNSEE (1988) Mexico City does not have a reticulated gas supply system. Instead, tankers supply LPG to storage tanks, commonly seen on building roofs.

Telecommunications

NZNSEE (1988) reported that the telephone system (above ground) was seriously damaged in the earthquake. The principal exchange building collapsed with ten fatalities, and many others were severely damaged. All damage to equipment was attributable directly to intense shaking. No fires occurred.

Transportation and roading

According to NZNSEE (1988) there was very little disruption to road or rail transport by the earthquake. However, in Mexico City many streets were blocked by rubble or collapsed buildings, or suffered collapsed pavements, but there were readily available alternative routes because of the flat terrain.

Damage to structures

According to EARTHQUAKE SPECTRA (August 1988) this earthquake was exceptional:

- it led to the largest toll of collapsed structures produced by a single event in the country
- it was one of the largest experienced by a modern city built in accordance with advanced seismic design provisions.

NZNSEE (1988) reported that the observed effects of this earthquake provided clear examples of almost every known cause of poor seismic performance, especially in multi-storey construction. Severe damage generally occurred where structures with poor seismic resistance were built on ground which strongly amplified the earthquake motions.

EARTHQUAKE SPECTRA (August 1988) reported that although damage in the coastal region was moderate to light, in Mexico City over 200 multi-storey buildings collapsed. According to this source, on the basis of conventional criteria for estimating the ultimate capacity of structures to resist earthquakes it was readily concluded that in the soft soil areas in Mexico City the intensities reached values much higher than the building regulations anticipated.

Cassaro & Romera (1985) reported that the earthquake shook various types of buildings until they collapsed, or were pounded to destruction by blows from adjoining buildings that were also rocked. Small buildings lay crushed beneath taller structures that had toppled.

According to NZNSEE (1988) surprisingly few examples of damage to, or failure of building services were reported or observed, even though there was negligible evidence of seismic restraint of items of building services plant, pipework or ducting.

	<p>This source considered the lack of damage to building services probably resulted from the predominant long period characteristics of the earthquake.</p>
Fire following earthquake	<p>NZNSSEE (1988) noted the following about post-earthquake fires:</p> <ul style="list-style-type: none"> • within 24 hours following the earthquake about 200 fires were reported • there was no major conflagration, presumably due to the type of construction (eg. absence of wooden buildings), and the absence of buried gas pipelines to cause extensive explosions • the fires played no part in the structural damage, but they probably killed trapped people who otherwise may have been saved • the only serious fire reported was due to a leak in the gas storage tank in the St Regis Hotel; the fire spread to an adjacent department store and to an office building occupied by a government department.
Fire causes	<p>According to NZNSSEE (1988) there were no fires fed by gas from leaking or ruptured gas mains. However, the leak in the St Regis Hotel LPG storage tank caused a major fire, as noted above.</p> <p>No other reference source identified post-earthquake fire causes, although it may be assumed (given the earthquake occurred at about breakfast time for many) that cooking appliances were in use.</p>
Fire spread mechanisms	<p>With the exception of the NZNSSEE (1988) reference to the St Regis Hotel fire, no other reference source identified instances of fire spread beyond the structures of fire origin.</p>
Damage to fire safety systems	<p>No reference source provided information on this issue.</p>
Effect of earthquake on water supplies	<p>NZNSSEE (1988) reported that the earthquake caused damage below ground which was just as devastating as the structural damage at the surface: water system pipes were seriously damaged.</p> <p>The damage to water mains occurred in the central city area in the zone of building damage, and also in the south-east section of the city. The types of underground water line failures reported were:</p> <ul style="list-style-type: none"> • shear failure (in the large diameter pipes) • telescopic failures in smaller diameter pipes. <p>This damage resulted in:</p> <ul style="list-style-type: none"> • complete loss of water supply to four suburbs • severe curtailment in six other suburbs • a process of pipeline repair which took in excess of a year, and in the early stages water was supplied to temporary tanks supplied by tank trucks.
Response of the fire department	<p>According to NZNSSEE (1988):</p> <ul style="list-style-type: none"> • Fire Department Headquarters building was damaged by the earthquake, and this caused a delay in organising fire services • the lack of water due to broken mains and distribution pipes in and around collapsed buildings could also have adversely affected fire-fighting ability. <p>No other reference source provided information on this issue.</p>
Lesson to be learned	<p>NZNSSEE (1988) considered that the most striking aspect of the underground damage to water lines due to this earthquake was that the damage area was much larger in size than the area of above-ground structural damage. It suggested that underground utility pipes are even more vulnerable to earthquake damage than buildings.</p>

The earthquake caused a disastrous loss of telecommunications facilities in Mexico City. To ensure the continuing availability of telephone communications after an earthquake event and for victims seeking the emergency services including fire department assistance, telecommunications equipment sites and networks must be constructed so as not to be vulnerable to earthquake attack.

10. 1987 Edgecumbe, NZ, Earthquake

The earthquake	This earthquake is known as the Edgecumbe Earthquake, March 1987.
When	It occurred at 1:42pm on Monday, 2 March 1987
Magnitude	
Intensity	<p>Pender (1987) reported that it registered 6.3 on the Richter Scale. A foreshock of magnitude 5.2 occurred at 1:35pm. Four aftershocks with magnitudes in excess of 5.0 occurred later on the day of the main event.</p> <p>According to Smith (1990) the intensities experienced near the epicentre of this earthquake were higher than expected for an event of magnitude 6.3. Although not a large earthquake it caused MM IX in and near the town of Edgecumbe. Ground motion was unusually strong with resulting serious damage.</p> <p>Dowrick (1987) reported that this earthquake was New Zealand's most damaging since the great Hawkes Bay earthquake of 1931, despite it being of only moderate size and despite the rapid attenuation of intensity with distance from the centre.</p>
Location of epicentre	According to Smith (1990) the epicentre was located near Edgecumbe and the depth of the focus was 8km.
Area affected	From Smith's isothermal map for the event it was deduced that the earthquake was felt across the Rangitaiki Plains with intensities of MM VI and MM VIII at Rotorua and Whakatane respectively.
Earthquake expectancy	According to Dowrick (1987) the significance of this earthquake arises mainly because the country had been experiencing a relatively quiet period of seismic activity for the past half century.
Demographic detail	None of the references available gave this data.
Geotechnical perspective	<p>Dowrick reported that this earthquake resulted from a normal fault rupture but produced spectacular surface downthrow displacements and wide cracks.</p> <p>Pender (1987) reported extensive evidence of level ground liquefaction and lateral spreading near rivers.</p>
Human toll	According to Billings (1991) only 3 of over 1,000 people working on-site at Tasman Pulp & Paper Co. were injured in spite of the extensive damage suffered at this site. According to Voss (1987) that there was no loss of life was remarkable.
Economic loss	Billings quoted capital costs for damage reinstatement at Tasman Pulp & Paper Co. as \$44million, and \$68million loss of production costs. No other damage costs were advised in the references available.
Infra-structure damage	<p>Dowrick (1987) reported that transformers had been shaken from their bases and overturned at the Bay of Plenty Electric Power Board's Edgecumbe substation.</p> <p>According to ESAANZ (1987) the earthquake caused extensive damage to the electrical supply system but most areas had power restored within two days of the earthquake.</p>
Damage to structures	According to Dowrick there was a wide range of performance of structures and equipment in the strong-motion zone, ranging from no damage to total destruction, depending on the type of construction and the location. Industrial

structures suffered the heaviest damage.

Billings reported extensive damage to structures and key plant items at the Tasman Pulp & Paper Co. Ltd. mill at Kawerau.

According to Pender (1987) only a few hundred homes sustained structural damage, and less than 50 suffered substantial structural damage.

Fire following earthquake

No fires were reported in the references available, but a detailed account of sprinkler system damage was given which indicated that had fire broken out in many buildings it might not have been controlled by the fire sprinkler system (refer below to "Damage to fire safety systems").

Fire causes

Although no post-earthquake fires were reported, Voss (1987) noted that many buildings were at their greatest risk from fire immediately following the earthquake due to the common causes of fire that were found during post-event site inspections, as follows:

- fuel lines were leaking
- electrical cabling strained (and having the potential for causing shorting or arcing).

During the earthquake many occupants would have been pre-occupied with escaping from buildings, and ignitions (had they occurred) may not have been noticed.

Fire spread mechanisms

Not relevant to this earthquake.

Damage to fire safety systems

Voss (1987) reported that although many buildings which were damaged remained standing, the sprinkler systems within them did not, generally, remain intact. Thus, had fire broken out within these buildings, it might not have been controlled by the fire sprinkler systems, and the final damage bill would have been much greater.

According to Billings (1991) in many areas of the Tasman Pulp & Paper Mill sprinkler pipes and fittings fell to the ground.

Voss reported that of those systems surveyed for earthquake damage, all the severely damaged systems were designed and installed under the the Provisional NZ Standard Specification for Automatic Fire Sprinkler Installations, NZS 4541P:1972 (except for 3 or 4 in number which pre-dated the publication of that standard). His observations were:

- extent of damage was independent of the age of the system (severity of damage was associated with the design of the pipe runs and the fixings than the age and condition of the pipes)
- extensive failures occurred due to lack of adequate sway bracing (wherever the larger pipes in a system, especially cross mains, were able to move independently of the supporting structure, damage resulted)
- screwed joints weakened the pipe as a structural element and were not considered an appropriate method for joining medium weight pipe where seismic resistance was required (although many of the failures would not have occurred had sway bracing been provided, there would have been fewer failures of range pipes had the piping been fully welded)
- screwed joints aggravate corrosion problems in aggressive environments, since the base metal in the thread cannot be adequately protected in service
- system piping designed to accommodate movement between parts of a building, using proprietary mechanical joints, was generally undamaged
- installations which did not allow for differential movement between the respective parts of buildings to which it was attached were ruptured by the building movement

- underground piping of sprinkler water supplies, which included asbestos-cement pipes, failed due to shear failure arising from inherent brittleness; steel pipe and PVC pipe generally behaved well.

Voss gave some details on the requirements of the Standards current at that time, and how they were generally used:

1. NZS 4541P:1972
 - required the sprinkler system to be designed to withstand earthquake movement
 - the means of compliance were not specified (left to the discretion and judgement of the designer)
 - the usual approach where a design for earthquake resistance was done was to use a design based on “equivalent static forces”, (that was also required for structural design by NZS 4203: 1976).
2. NZS 4541:1987. This superceeding sprinkler standard required:
 - hangers be designed to carry vertical loads in tension only (therefore, if large horizontal loads are applied to hangers, failure by bending or shear results)
 - underplayed the importance of sway bracing in the earthquake resistance of sprinkler systems, by its vagueness in its treatment of it
 - although maximum limits were set on pipe spans it was left to the designer to detail sway bracing.
3. NFPA 13.
 - set out the requirements for sway bracing
 - prescribed the means of compliance in much greater detail

According to Voss, generally those systems covered by the survey which were constructed in such a way that they would have complied with NFPA 13 withstood the earthquake. Conversely, those systems that did not comply with NFPA 13 did not survive the earthquake.

Effect of earthquake on water supplies

Pender (1987) reported that over 400 breaks in water supply and sewerage lines had to be repaired before the state of emergency could be lifted in Edgecumbe, and that took more than two weeks.

None of the references available reported the extent of disruption to fire-fighting water supplies, nor what demands, if any, were placed on them.

Response of the fire department

No post-earthquake fires were reported in the references available.

Lessons to be learned

As reported by Voss (1987), the sprinkler system must be designed to a higher seismic standard than the building itself. Although many of the buildings which were damaged remained standing, the sprinkler systems within them did not. Thus had fire broken out within these buildings, it might not have been controlled by the sprinkler system.

According to Voss, this earthquake highlighted reasons why automatic sprinkler systems should be so constructed as to survive without impairment under earthquake conditions (providing the building is still erect after an earthquake):

- to ensure the protection and preservation of the means of egress, by allowing human occupants to escape from fire and have the benefits of sprinkler protection, where necessary
- to avoid impeded egress by occurrences such as water leakage blacking out lighting (by tripping electrical circuits), and obstructing stairways with high water flows

- to avoid the consequential damage to flooring, building linings and insulation, electrical switchgear and machinery, finished product and raw materials (water damage due the structural collapse of sprinkler piping can be as costly and disruptive as fire)
- to avoid the diversion of water away from the design operating area of the system (with loss of ability of the sprinkler system to control its design fire), as a consequence of occurrences such as main supply pipe breaks.

11. 1987 Whittier Narrows, Los Angeles, Southern California

The earthquake	Known as the Whittier Narrows earthquake.
When	This earthquake occurred at 7:42am, on October 1, 1987.
Magnitude	
Intensity	According to Shepherd (1987) this earthquake was of Richter magnitude 5.7, and was followed by a major aftershock of Richter magnitude 5.5 at 3:59am on October 4. EARTHQUAKE SPECTRA (Feb. 1988) reported that the Oct. 1 event maximum intensity assigned to the Whittier area was MMI VIII. In comparison to the 1971 San Fernando earthquake the Whittier Narrows event had an energy release of about 10% of the San Fernando earthquake.
Location of epicentre	Shepherd (1987) reported the epicentre to be west of Whittier, some 14 km. below ground surface. There was 4 seconds of strong shaking at Whittier, with horizontal ground level motion peaks of 0.6g and a vertical component of 0.09g.
Area affected	According to EARTHQUAKE SPECTRA (Feb. 1993) the event was centred in an older developed area in the eastern part of Los Angeles County, and not under an urban centre. However, it caused considerable damage to buildings and urban infrastructure in adjoining urban areas. Smoke (1988) reported that although the impact was greater in Whittier and other communities, it was felt generally throughout Southern California.
Demographic detail	EARTHQUAKE SPECTRA (Feb. 1988) estimated the total population in the entire impacted area suffering intensities between MMI VI and MMI VIII at almost 7 million.
Geotechnical perspective	Shepherd (1987) reported that the earthquake occurred on a previously unidentified fault, and suggested that has implications for downtown Los Angeles insofar as it has not been thought to be in immediate proximity to an identified fault.
Human toll	According to EARTHQUAKE SPECTRA (Feb. 1988) three fatalities occurred on October 1 during or immediately after the main shock. In excess of 1350 people were injured.
Economic loss	EARTHQUAKE SPECTRA (Feb. 1988) reported losses to be in excess of \$358M, with private sector losses constituting just over two thirds of this amount.
Infra-structure damage	Power system. Overall power system performance as measured by customer service disruptions was good, according to EARTHQUAKE SPECTRA (Feb. 1988), although it reported power was lost to about 37,000 customers in the City of Los Angeles due to a transformer fire fuelled by an oil leak. In the Los Angeles County there were numerous disruptions of power for varying periods in the service areas affected by the earthquake (most due to burn-down, and wrapping of lines). Gas distribution EARTHQUAKE SPECTRA (Feb. 1988) reported about 1,400 gas leaks, with 75% being due to leaks from water heater appliance connections. A public service announcement immediately after the earthquake advised people to shut the gas off to their homes (however, the response to this and its effect was not reported).

Damage to structures	<p>EARTHQUAKE SPECTRA (Feb. 1988) reported that an estimated 10,000 commercial and residential buildings were damaged in the earthquake.</p> <p>According to Shepherd (1987) many pre-code buildings in Whittier, in the area of severest shaking, either collapsed or were weakened to become unsafe for occupation.</p> <p>Smoke (1988) reported that in excess of 200 buildings were declared unsafe.</p> <p>It was also reported by Shepherd (1987) that some downtown Whittier commercial buildings (some dating back to the early 1990's) had no structural strengthening. Also, some buildings constructed 20 - 30 years ago suffered significant damage, indicating likely deficiencies of structures designed to earlier codes. One such complex was the campus of California State University at Los Angeles, about 6 km from the epicentre, where substantial structure damage was sustained by beams, columns and shear walls.</p>
Fire following earthquake	<p>Smoke (1988) reported that during the first five hours following the earthquake Los Angeles Fire Department responded to 75 gas fires and 38 other structure fires, but no large-scale fires occurred. By 1:00pm (approximately 5 hours after the earthquake) the worst appeared to be over.</p> <p>The Los Angeles County fire Department were called to 54 gas leaks (it was not clear how many of these involved fires, if any), 19 structure fires, and 170 rescue operations.</p>
Fire causes	<p>EARTHQUAKE SPECTRA (Feb. 1988) reported 20 earthquake-related structure fires occurred in the Los Angeles County fire Department area (10 of these were in the Whittier area).</p> <p>EARTHQUAKE SPECTRA (Feb. 1988) reported fire causes:</p> <ul style="list-style-type: none"> • arcing and shorting when power was restored to damaged electrical appliances or fallen light fixtures • one fire resulted from the movement of combustible material towards a heater by earthquake motion • one fire resulted from the mixing of spilt chemicals • burned-down power lines (overhead lines making contact due to earthquake-induced motion, burning through the conductors and causing them to drop). These created a fire (and shock) hazard, caused two grass-land fires by arcing to ground (circuit not tripped due to high resistance contact), and lead to most of the longer service disruptions.
Fire spread mechanisms	<p>No mention was found in the reports available to indicate fire spread beyond the structures of fire origin.</p> <p>Smoke (1988) reported no large scale fires occurred.</p>
Damage to fire safety systems	<p>EARTHQUAKE SPECTRA (Feb. 1988) reported that several structures had leaking fire sprinkler systems. Some were due to sprinkler heads that were knocked open, while others had leaking pipes.</p>
Effect of earthquake on water supplies	<p>According to EARTHQUAKE SPECTRA (Feb. 1988) water systems in the region performed well and there was little disruption to service from damage to transmission or distribution systems. However, according to that report Whittier experienced the most serious damage with several dozen watermain breaks and leaks, and the peak water pressure only at about 50% of its normal level during the two days following the earthquake. As a consequence, limited areas were without fire-fighting water for periods of hours.</p>

**Response of the
fire department**

EARTHQUAKE SPECTRA (Feb. 1988) reported that when the main shock struck at 7:42am many emergency response units (particularly fire and police) were part way through a shift change and were at double strength.

According to Smoke (1988), during the day of the earthquake Los Angeles Fire Department had responded to 1,185 incidents (nearly twice the normal load). During the period of greatest demand about half of the Fire Department fire suppression companies were committed .

EARTHQUAKE SPECTRA (Feb. 1988) also reported a maximum commitment of units of 50% of those available, but noted that some fire calls did not receive a response for as long as an hour after the report was received. According to that source, the Emergency 911 service remained operational, although saturated with calls, but it was not clear how much of this delay was due to the dispatch system and how much was due to difficulty in travelling to the fires.

According to EARTHQUAKE SPECTRA (Feb. 1988) the disruptions to water supply in the Whittier area did not cause any problems for the Los Angeles fire Department.

**Lessons to be
learned**

EARTHQUAKE SPECTRA (Feb. 1988) reported that a significant number of gas and water leaks were associated with the motion of water heaters, which places a large load on rigid gas and water connections. It suggested that methods of immobilising water heaters should be improved.

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12. 1989 Loma Prieta, Northern California Earthquake

The earthquake	Loma Prieta earthquake.
When	This earthquake occurred at 5:04pm, Tuesday October 17, 1989.
Magnitude	
Intensity	<p>According to Lew (1990) this earthquake had a Richter magnitude of 7.1 and was the largest earthquake to strike Northern California since the great San Francisco earthquake of 1906.</p> <p>EERI (1990) reported that to date this earthquake was one of the largest to affect a major urban area in the United States in this century. Although it resulted in only moderate shaking for most of San Francisco, typically of MMI VI, selected areas sustained much greater shaking, perhaps as much as MMI IX in the Marina district.</p> <p>Blackburn (1990) reported that peak ground acceleration was estimated to be 0.3g horizontally in the Marina district.</p>
Location of epicentre	Scawthorn and Khater (1992) reported the epicentre to be in a remote area of the Santa Cruz Mountains, 56 miles southeast of San Francisco.
Earthquake expectancy	According to Blackburn (1990) this earthquake was a disaster and experts had expected such an event, however, society in general was not prepared for it.
Geotechnical perspective	Lew (1990) reported that most structural damages in the Bay area occurred to structures sited on deep deposits of overburden soils above the bedrock. The intensity of bedrock shaking was much higher in the Bay than in other directions from the epicentral area possibly due to directional characteristics of the rupture. Ground failures, including landslides and liquefaction, were frequent in both epicentral and Bay areas.
Human toll	According to Lew (1990) the Loma Prieta earthquake caused 62 fatalities due to partial or total collapse of older structures, injured 3,757, and left 12,000 people homeless. Landslides caused 2 deaths, and fire claimed one life. The unusual event of coincidence was a Bay area World Series baseball game which reduced traffic far below normal levels on the I-880 viaduct which collapsed to cause most of the life losses.
Economic loss	Lew (1990) reported the direct property losses were in excess of 1990 \$US6 billion.
Infra-structure damage	<p>Blackburn (1990) reported that power supplies to the communities were immediately shut down. There was very little permanent damage although some outages lasted several days. Earthquake damage also caused a disruption of the piped water system, both low and high pressure systems.</p> <p>According to Lew (1990) gas mains were also disrupted and gas leaks were prevalent, although the removal of power sources and the caution exercised by the citizens was effective in preventing ignition of leaking gas.</p>
Damage to structures	<p>According to Blackburn (1990) little of the damage in this earthquake was unexpected to the engineering and technical communities.</p> <p>Lew (1990) reported that most structures designed in accordance with modern codes and standards performed well without serious damage in both epicentral and Bay areas. However, there were many concrete and masonry buildings and highway structures in the San Francisco Bay area which were not designed according to modern seismic design codes and which did not perform well.</p>

Many buildings in urban areas were damaged by pounding against adjacent buildings.

Fire following earthquake

EMERGENCY (1989) reported that in the first two hours after the earthquake, 27 fires broke out, most from natural gas leaks.

According to Coleman (1994) San Francisco had 27 structural fires during the first seven hours. The largest fire started by the earthquake was in the densely built Marina District, which was subjected to relatively strong shaking, and began in a heavily damaged 1920's style four-storey timber framed building containing 21 apartments. This fire spread to and destroyed a row of about eight apartment houses.

In Berkeley, a major fire in an auto-service building required the response of the entire Berkeley fire department.

Santa Cruz County, closer to the epicentre, reported more than 20 fires. The City of Santa Cruz lost only one residential structure, due to a gas main leak, and was fully involved on fire department arrival.

In Santa Clara County a ruptured propane tank ignited a residence fire. The water distribution system for the community had been destroyed, so water was drafted from the community swimming pool.

Fire causes

According to Lew (1990) the shut-down of the electric power eliminated this as an ignition source and caused all electricity powered safety valves (eg safety pilots on water heaters etc) to close, shutting off the pilot and interrupting the flow of gas at that point. It is believed that this action prevented many ignitions in those buildings where there was enough movement to break the internal pipes and sever the electrical wiring. Additionally, the caution exercised by the citizens was effective in preventing ignition of leaking gas.

The actual ignition source of the fire in the Marina District was not identified in the articles reviewed by the writer, although it is suggested that cooking appliances (providing hot surfaces, naked flame etc.) would have been in use given the time of the earthquake.

Coleman (1994) reported that beyond San Francisco, a major fire in Berkeley involving an auto-service building started from the ignition of spilled solvents.

Fire spread mechanisms

EMERGENCY (1989) referred to the apartment building fires in the Marina District and identified radiant heat as the cause of fire spread to adjacent buildings.

According to Lew (1990) at the time of the earthquake and through the next several days there was little wind. This was felt to have been an important factor in the fire which occurred in the Marina District. Had there been a wind, it is quite possible that fire could have developed into a multi-block conflagration. In addition, rains immediately prior to the earthquake had resulted in a high moisture in the ground and wild lands. In areas such as the Santa Cruz mountains, there were ignition sources resulting from downed power lines. Some minor fires did occur. One was significant but still localized. This reference predicted that had the hills been dry and/or a strong wind been present, a different result could well have occurred.

Damage to fire safety systems

Lew (1990) reported that private fire protection systems such as sprinklers, standpipes, and alarm systems for the most part were not interrupted. This was probably due to both of the following aspects:

- the earthquake bracing requirements included in the fire protection standards governing the installation of these devices in earthquake zones

- most of the buildings where such equipment was involved did not suffer extensive structural damage.

Blackburn (1990) also reported that fixed fire protection survived well with certain exceptions, given as:

- several broken water mains supplying building sprinkler systems in areas of infirm soil
- broken sprinkler piping at the airport terminal
- damaged roof tank in a multi-storey building in the financial district.

Such systems were readily isolated and townmain breaks could be compensated for where the break was before the shut-off valve or check valve on the supply main that the fire service inlet was located in. This emphasises the importance of these valves in building sprinkler systems when the external supply fails, to avoid water flowing out of sprinkler systems.

Effect of earthquake on water supplies

Blackburn (1990) reported that water mains throughout the City broke in areas of filled or infirm soil. The Marina District was severely impacted by 69 breaks in the high pressure water mains (fed from the City-wide Auxiliary Water Supply System or AWSS), and affecting the supply to fire hydrants in a 44 square block area. The low pressure system mains (Municipal Water System) suffered 98 breaks, with 45 service connections damaged as well, and these quickly dissipated all domestic water supply. These disruptions of the piped water system, both low and high pressure systems severely affected fire-fighting operations in the Marina District and the outlying residential district in the southwest section of the city.

According to Blackburn the AWSS also experienced one main break (12" main), one 8" hydrant branch break, and base elbows to 5 high pressure hydrants broken, all in the South of Market infirm area.

Blackburn noted that the high pressure system is a separate system of pipe lines owned and operated by the Fire Department. It is valved so that they can be readily operated to isolate breaks when necessary. It is divided into three zones based upon contour elevations so that tanks and reservoirs can provide gravity flow at high pressure to hydrants. The lower zone was temporarily rendered inoperative immediately following the earthquake due to the volume of water flowing from the breaks in the South of Market district. This loss of water supply immediately affected fires that occurred in the Marina District.

EMERGENCY (1989) reported that water was finally secured from the fireboat "Phoenix" and delivered to the fireground more than six blocks away by four 5" diameter hose leads. It was claimed that had it not been for the fireboat the Marina District would have been lost. As it was the fire was confined to one square city block.

According to Coleman (1994) the Marina Fire was under control at about 8:00pm. Before all fire operations were concluded in the Marina District the fireboat pumped 6,000 gpm for more than 18 hours.

EERI (1990) reported that in addition to the AWSS, which feeds the street hydrant system, San Francisco has about 245 underground cisterns and the Portable Water Supply System (PWSS).

EERI described the cisterns as being:

- typically of concrete construction and 75,000 gallons capacity (about a one hour supply for a typical fire department pumper)
- located at street intersections and accessible by a manhole completely independent of all piping and filled by hose from fire department pumps supplied from hydrants.

In the event of AWSS main failure, water may be drafted from these cisterns. EERI described the PWSS as consisting of large diameter (5") hose which is carried on hose tenders, together with portable hydrants, pressure reducing Gleeson valves and other fittings. Each hose tender carries about 5,000 ft of hose, and is capable of laying this in about 20 minutes. Hose lengths are intermittently fitted with the portable hydrants, permitting water supply at many locations along the hose. Water can be pumped into the system by fire department pumpers, or the fireboat drafting from the harbour.

**Response of the
fire department**

EERI (1990) reported that the fire-fighters in the Marina District were hampered in suppression efforts because the water supply from the hydrant system was inadequate due to the earthquake damage to the water mains in the area. Although the AWSS pipe network failed in the short term due to the small number of breaks (previously described), the fireboat / PWSS back-up system proved its flexibility and effectiveness. Although the fire had grown to a large size (report of the fire had been delayed) it was suppressed before it spread beyond the block. The successful suppression efforts, and the unusual lack of wind at the time of the fire prevented the conflagration and possible the loss of several city blocks which it is claimed would most assuredly have resulted, had the prevailing stronger wind conditions been present. Also, had greater fire spread occurred in the Marina, and perhaps with other fires in San Francisco due to the earthquake, it is likely the fire department resources would have been overwhelmed.

According to EMERGENCY (1989) the San Francisco Fire Department (SFFD) Despatch Computer went down due to overloading about five minutes after the earthquake struck. Units were manually dispatched until the call volume subsided.

Blackburn (1990) reported that the immediate loss of electric power to the City and to 2/3 of fire stations caused severe disruption of operations.

According to Blackburn, within four hours of the earthquake the SFFD responded to 400 calls including 22 fires. The SFFD had 41 Engine Companies and 18 Truck companies, 2 Rescue Companies, 1 Fireboat and 296 personnel on duty.

Blackburn identified the critical problems with resources as:

- on-duty staffing of the Department was insufficient to handle the problems encountered (the Department had just been reduced in daily staffing July 1, 1989 from 315 to 296)
- insufficient amount of reserve apparatus coupled with excessive age of its apparatus fleet (average age of all pumpers 12 years) and no reserve aerial trucks with operational aerial ladder (it was necessary to have two vehicles from the department Museum brought back into service during the emergency)
- Department radio communications quickly became very difficult due to complete overload from insufficient radio channels for the amount of traffic
- inadequate availability of fuel to refuel apparatus, and this was reaching crisis proportions when the event subsided
- inadequate supply of flashlight batteries and small equipment such as nozzles and fittings for reserve apparatus
- lack of material for quickly shoring up collapsed buildings.

Additionally, internal coordination and communications during the critical hours following the earthquake were at times chaotic and did not function as well as desired.

Lew (1990) also reported that Fire Department radio communications were so overtaxed as to be of greatly reduced value.

Lessons to be learned

According to Lew (1990):

- this earthquake did not place as much stress on the fire-fighting system as a major earthquake would have
- if a major earthquake were to occur, the increased level of destruction of buildings and the resulting increase of available fuel and ignition sources would probably increase the number of fires
- if electric power is removed promptly following a major earthquake (as it was following the San Francisco earthquake), it is likely that many of the potential sources will be interrupted (as apparently occurred in the San Francisco earthquake)
- the underground water distribution and gas distribution systems are very vulnerable, and generally showed extensive failure even in this moderate earthquake
- it appears that advances in survival of these systems has not matched the advances in the survival of structures
- the development of better means to insure continued fire-fighting water supply and preventing or minimising the leakage of gas from the distribution system is critical.

According to Blackburn (1990) improvements are necessary, many lessons were learned. With this in mind, continued planning, training, increased staffing, upgrading of equipment and provision of additional emergency water supplies for San Francisco are vital.

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13. 1993 Hokkaido Nansei-oki, Japan Earthquake

The earthquake	Although this event is known as the Hokkaido Nansei-oki Earthquake it is also referred to as the Hokkaido Southwest Offshore Earthquake.
When	This earthquake occurred at 10:17pm, Monday July 12, 1993.
Magnitude	According to EARTHQUAKE SPECTRA (April 1995) this earthquake had a Richter magnitude of 7.8 and was the largest to strike Japan in the past 15 years.
Intensity	Scawthorn (1993) reported that it caused 60 secs. of moderately strong ground shaking over an area of about 100 x 150 km in south-western Hokkaido. A peak ground acceleration of 0.5g was recorded about 100km from the edge of the offshore aftershock zone. The initial shock was followed by a large tsunami which hit the coast of Okushiri Is. less than 5 minutes after the earthquake, and which caused water run-ups typically 5 - 12m high in the settled areas along the coast of Okushiri Is.
Location of epicentre	According to EARTHQUAKE SPECTRA (April 1995) the epicentre was about 80 km west of Hokkaido Is. at a depth of about 27 km in the Sea of Japan
Areas affected	Hokkaido Island in Northern Japan, and Okushiri Is. a small island south-west of Hokkaido and 48 km south of the epicentre.
Earthquake expectancy	Earthquakes are felt frequently throughout Japan, but this event was the second large earthquake to hit the area during 1993. According to NZNSEE (1994) the Kushiro Offshore earthquake occurred to the east of Hokkaido Is. on January 15, 1993, and also registered Richter magnitude 7.8. Unlike the Hokkaido earthquake it did not cause a tsunami because of its depth of about 107 km. However, its felt intensity in Kushiro City was MM9 - MM11, but damage was less severe than expected and only two lives were lost and only a few structure fires occurred.
Demographic detail	According to EARTHQUAKE SPECTRA (April 1995) Okushiri Is. had about 5,000 residents, mostly located in three small fishing villages. Aonae, one of these villages had a population of about 1,600. No population data was located for the those earthquake-affected areas of Hokkaido Is.
Geotechnical perspective	<p>EARTHQUAKE SPECTRA (April 1995) reported that the earthquake caused widespread liquefaction in the south-western part of Hokkaido and in one location on Okushiri Is. near Aonae airport.</p> <p>Scawthorn (1993) reported extensive damage was due to ground failures, including liquefaction, lateral spreading, settlement and land sliding. Large landslides occurred throughout the strongly shaken areas of Okushiri and Hokkaido Islands.</p>
Human toll	<p>According to NZNSEE (1994) most of the loss of life occurred on Okushiri Is. as a result of the tsunami. There were also fatalities due to tsunami in coastal areas of western Hokkaido, and on the Pacific coast of Russia.</p> <p>About 242 lives were lost as a result of the earthquake, and only two could be attributed to fire.</p>
Economic loss	Scawthorn (1993) reported that most of the financial loss was from the damaged caused by the tsunami, which was concentrated on Okushiri Is. and along the west coast of Hokkaido Is. opposite the fault rupture. The total dollar loss was placed at around 1995 NZ\$612M.

Infra-structure damage	<p>According to EARTHQUAKE SPECTRA (April 1995), Okushiri Is. was devastated by the earthquake and by subsequent damage from the tsunami.</p> <p>Scawthorn (1993) reported that earthquake shaking on Hokkaido Is. caused railways to be disrupted at 124 locations, and highways were damaged in at least 365 locations. Serious damage occurred to schools, industrial structures, bridges, port facilities, and all other types of infrastructure.</p> <p>Widespread liquefaction caused the buoyant rise of manholes and buried tanks, and seaward tilting of quay walls, but there were no major disruptions to port facilities. Several bridges suffered minor damage, and there were many instances of settlement of bridge approach fills.</p>
Damage to structures	<p>Scawthorn (1993) reported that 31 public buildings were damaged on Hokkaido Is, some severely.</p> <p>Overall, tsunami destroyed 540 houses, significantly damaged 154, and partially damaged 1826.</p>
Fire following earthquake	<p>Fire followed the tsunami in Aonae and destroyed much of the town. According to NZNSEE (1994) no other fires were reported in the many other towns and villages (approximately 30) on Hokkaido and Okushiri Islands.</p> <p>Scawthorn (1993) reports that the Aonae fire started at about 10:40pm, approximately 23 minutes after the initial earthquake, and about 16 minutes after the tsunami arrived. Two hours into the fire, a second fire ignited behind the fire line.</p> <p>According to EARTHQUAKE SPECTRA (April 1995) the Aonae fire eventually consumed 190 houses and buildings over an 11 hour period. Scawthorn (1993) noted that most of the town was on the beach and only a few metres above sea level. Commercial occupancies were closer to the wharf area, and residential at the base of a bluff. Many buildings were of mixed occupancy. The rest of the town was located on the bluff where a lighthouse, the town offices and the fire station were sited.</p> <p>The lower part of Aonae was densely built-up with narrow streets and typical building spacings of about 3m. Buildings were generally of post and beam construction, one or two storey, and with non-combustible stucco or cement board exterior linings over wood. There were large amounts of exposed wood trim, and corrugated roofing was common.</p>
Fire causes	<p>According to Scawthorn (1993) fire began as the result of earthquake damage. Fuel of first ignition and ignition source are unknown, but numerous ignition sources were available, particularly from cooking and heating appliances.</p>
Fire spread mechanisms	<p>EARTHQUAKE SPECTRA (April 1995) reported that the principal mechanisms of building-to-building fire spread involved:</p> <ul style="list-style-type: none"> • ignition of exterior wood trim • radiant ignition of combustible contents through windows • fire spread along scrap wood between buildings • burning kerosene and propane tanks. <p>Typically each home had an outdoor 490 litre kerosene tank for heating, generally located in an unanchored steel rack, and also a pair of propane tanks for cooking, typically 20 kg each and also not normally anchored.</p> <p>Scawthorn (1993) reported that fire progress was aided by flammables stored in each home, considerable scrap wood in and among buildings, numerous</p>

vehicles, and also the many outdoor kerosene and propane tanks. Eight kerosene tanks were found empty after the fire, most having vented through the top vent pipe (caused by radiant heat boiling the kerosene). Two ruptured kerosene tanks and eight exploded propane tanks were also found.

EARTHQUAKE SPECTRA (April 1995) reported that at the time of ignition wind was at 1.5 m/s, with gusts up to about 5 m/s. Fire progress was relatively slow (estimated at 35 m/hour) and was significantly impeded by suppression efforts, but fire-fighters were unable to stop the fire due to the successive involvement of the outdoor fuel tanks.

Also reported were the significant quantities of burning wood and embers flying through the air, but they did not play a major role in the fire spread because most of the buildings had metal roofs, and there were no roof vents through which the brands could enter attics.

Damage to fire safety systems

No reports were available on this issue. It is assumed that only passive fire protection systems associated with the non-combustible outer cladding of buildings and non-combustible materials of construction such as masonry, provided any benefits to resisting ignition and fire spread.

Effect of earthquake on water supplies

No reports were available on the impact of earthquake shaking on water supplies.

However, Scawthorn (1993) reported that fire hydrants were located around Aonae but were not used to provide water for fire control because the water mains were insufficiently sized and pressured. The main fire emergency water was stored in four 40,000 l underground cisterns sited throughout the town, and accessed through concrete manhole covers. The condition of these was not reported, but it was noted that water was drafted from them for post-earthquake fire-fighting.

Response of the fire department

Scawthorn (1993) reported that the fire department at Aonae was staffed by one full time professional fireman and 38 trained volunteers (although only 11 fire-fighters were able to report for duty as many were away fishing). It was equipped with two engines of typical Japanese size and each fitted out with a pump of capacity 2,600 l/min, with 2,000 litre booster tanks, ten lengths of 20m-long 65mm diameter hose and two lengths of 4 m-long hard suction hose.

Scawthorn (1993) noted that at 4:00am, about six hours after ignition, the fire front was about 90 m wide and fire-fighting water from the cisterns was exhausted. Water was then draughted from the harbour by the two pumpers and delivered to the fire by four handlines. As the fire-fighters were unable to stop the fire due to the successive involvement of outdoor fuel tanks, a fire-break was created using equipment to move debris and two buildings in the path of the fire.

The fire was successfully stopped at about 9:00am the following day, having burnt for over 10 hours. Several dozen houses that were in its path were saved from further damage.

NZNSSE (1994) reported factors that influenced the approach to fire-fighting at Aonae:

- close proximity of houses and the narrow streets
- amount of debris which restricted road access by conventional fire appliances to the seat of the fire
- lack of back-up resources from other fire brigades on the island
- apparent inability to task helicopters with monsoon buckets for fire-fighting because of other priorities

- inadequacy of the reticulated water supply, and the commitment of resources to pumping from tanks and the harbour.

Lessons to be learned

The following ideas in relation to the lessons which could be learnt from the fire and the fire-fighting which followed this earthquake, are provided by the writer. As was to be the experience in the Kobe post-earthquake fires in 1995:

- it is impractical to stop fire spread in areas prone to conflagration risk without water supplies, and without adequate resources to pump water to the seat of the fire
- risk of urban conflagration was heightened in areas with housing of combustible construction, and which were close together
- fire spread by thermal radiation and direct flame impingement could have been countered by fire breaks, and non-combustible construction on a building-by-building basis
- outdoor storage of flammable liquids and gases in enclosures of fire-resistive construction could have reduced the risk of those fuels contributing to the fire load of the post-earthquake fires.

14. 1994 Northridge, San Fernando Valley, Southern California Earthquake

The earthquake	Known as the Northridge earthquake.
When	The earthquake occurred at 4:31am, Monday January 17, 1994.
Magnitude	According to EARTHQUAKE SPECTRA (April 1995) this earthquake had a Richter magnitude of 6.7 and was the same size as the 1971 San Fernando earthquake, but was more damaging because it caused stronger ground shaking and was located beneath the San Fernando Valley and a densely built-up area, and in the proximity to other communities in the Northern Los Angeles area.
Intensity	<p>This resulted in a shaking intensity which ranged over MMVII - MMIX. Peak ground accelerations exceeded 0.4g at many locations (maximum design value in the Building Code).</p>
Location of epicentre	According to EARTHQUAKE SPECTRA (April 1995) the epicentre was about 32km West - Northwest of Los Angeles in the San Fernando Valley at a relatively deep focal depth of 19km (which was deeper than any previous large earthquake in this region).
Area affected	US - JAPAN WORKSHOP (1995) reported that shaking intensities greater than MMI VIII were felt over approximately 700 sq.mi, and according to EARTHQUAKE SPECTRA (April 1995) it was felt as equal to or greater than MMI VII over approximately 1,200 sq.mi, of the Northern Los Angeles area.
Earthquake expectancy	According to EARTHQUAKE SPECTRA (April 1995) this earthquake was a surprise. It happened unexpectedly on a small local fault rather than along a major boundary. It also indicates a continuing high rate of seismicity along the northern edge of the Los Angeles basin.
Demographic detail	The 1990 population of the Los Angeles County was approximately 8.8M, and of Los Angeles City 3.5M.
Human toll	There were 58 fatalities and 1,500 serious injuries. According to EARTHQUAKE SPECTRA (April 1995) only one death was attributed to fire (an elderly woman in a mobile home blaze caused by a gas leak). It considered that given the severity and widespread damage and the size of the population at risk, the number of persons killed and injured was quite low. The time of the earthquake was fortuitous. Most people were in their homes, whereas had the earthquake struck later in the morning many more people would have been out of their homes in more hazardous settings (eg. shopping centres, parking structures, and highways that sustained serious damage), and which could have caused a large number of deaths.
Economic loss	EARTHQUAKE SPECTRA (April 1995) reported an estimated 1994 US\$20 billion in damage, and while not a catastrophic event by any standard it vividly demonstrated how disruptive even moderate earthquakes can be when they strike in highly urbanised areas.
Infra-structure damage	<p>Todd (1994) reported that in the epicentral region the earthquake caused extensive failures of control and distribution plant at electric switchyards (fractures of ceramic elements in circuit breaker assemblies), and ruptured both water and gas mains, and an oil pipeline in a suburban street.</p> <p>Chung (1995) reported that for the first time in Los Angeles history electrical power was out in the entire city. However, electric power service was restored to 90% of Los Angeles Department of Water and Power (LADWP) customers within one day of the earthquake.</p>

About 50,000 LADWP customers were without water on the first day of the earthquake. About 10,000 customers were still without water one week after the earthquake.

Damage to structures

THE ECONOMIST (1995) reported that no type of building came through the earthquake unscathed:

- at least 200 3-storey timber framed and stucco clad apartment buildings collapsed and a further 650 suffered serious damage
- a number of multi-storey car parks collapsed due to column failure
- many reinforced concrete office blocks older than 20 years performed badly, due to insufficient reinforcing
- moment-resisting steel framed buildings experienced welding failures
- six freeway bridges collapsed.

According to Todd (1994) damage to unreinforced masonry buildings was widespread. However, it reported that in many cases buildings designed and constructed in accordance with modern (mid-1970's or later) seismic requirements performed well structurally.

According to EQE Report (1994) three Los Angeles Fire Department (LAFD) fire stations received structural damage which caused their evacuation.

Fire following earthquake

US - JAPAN WORKSHOP (1995) reported approximately 110 earthquake-related fires in the earthquake affected area:

- 86% of these were structure fires
- of these, 60% were in single or multi-family dwellings
- all fires were out by noon.

Todd (1994) provided a timeline:

- time of earthquake 4:31am
- by 6:45am as many as 50 structure fires had been reported.
- by 9:45am all fires were under control.

The majority of the estimated 30 - 50 significant fires were located in the San Fernando Valley and were confined to the building of fire origin either by separation or by fire department action.

EARTHQUAKE SPECTRA (April 1995) reported that earthquake related fires made up most of the calls for the first three hours. During the remainder of the day the earthquake was a factor in about 40% of the fires (see Fire Causes below for the causes of new fires).

EQE Report (1994) noted some specific fire incidents as:

- most significant were three manufactured housing developments (mobile home parks) fires caused by the rupture of natural gas valves or mains (according to NIST SP 889 (1995) approximately 172 housing units were destroyed)
- several commercial structure fire losses
- a major hazardous materials fire in the science complex at California State University, Northridge
- incident on Balboa Boulevard in Granada Hills where gas escaping from a broken main beneath the street was ignited by a ute which had stalled in the water discharging from a fractured water main at the same location, and the inferno subsequently caused fires in five surrounding houses.

Fire causes

Todd (1994) reports the causes of fires as:

- natural gas leaks, being the principal cause
- hazardous chemical interactions, causing a small number.

US - JAPAN WORKSHOP (1995) notes the major causes of ignition were:

- electric arcing as the result of a short circuit
- gas flame from an appliance.

Todd (1994) reports that some fires which occurred in the days following the earthquake were directly attributable to the restoration of electricity and gas supplies shaken in the initial earthquake and the aftershocks. These fire incidents occurred at a greater than normal rate in the days following the earthquake.

Some of these were "red tagged" buildings which had been identified by authorities as unsafe to enter. Others were buildings which were either unoccupied or in which hazards had not been identified.

According to Todd (1994) natural gas is the predominant fuel used for space and water heating in the Los Angeles area and can therefore be found in most buildings. Although natural gas leaks may have played a role in a significant number of fires, this number was likely very small when compared with the total number of buildings exposed to significant shaking during the earthquake.

The report suggests that many fires may have been averted by residents shutting off the gas to buildings or appliances.

According to Chung (1995) the water heater was the most vulnerable appliance. It quoted SoCal Gas reports of approximately 2,500 water heaters being damaged in this earthquake. Approximately 20 fires were due to inadequately secured water heaters tipping over.

EARTHQUAKE SPECTRA (April 1995) reported that incendiary (arson) fires were not a major problem. In the three days following the earthquake eleven were considered as arson by Los Angeles City Fire Department (LAFD) (compare this with an average daily occurrence of about ten).

According to Todd (1994) no fires were known to have occurred at service stations, and because the earthquake occurred when most people were sleeping fire causes such as overturned candles and barbeque grilles were nearly non-existent, as were fires associated with industrial processes.

EARTHQUAKE SPECTRA (April 1995) reported the rupture of a 10" diameter oil pipeline in a suburban street and resulting in a massive spill of crude oil, which caught fire and sent walls of flame down the street destroying two houses and seventeen cars before the blaze was brought under control.

Fire spread mechanisms

Todd (1994) reported that most building fires were confined to the building of fire origin due to a combination of factors including:

- light winds, and favourable humidity and time of day
- building construction
- building separation
- the actions of the fire department.

However, in the fire incidents at the three manufactured housing developments Todd (1994) reported that the method of building-to-building fire spread was primarily through windows. Once a unit became completely involved in fire the thermal radiation was sufficient to cause the breakage of windows in an adjacent unit, or to ignite combustibles within the unit directly through the windows. Fire spread was stopped either by separation such as roads or open spaces, or by fire-fighting operations. Post-earthquake conflagration did not develop.

**Damage to fire
safety systems**

Todd (1994) reported that many sprinkler systems in buildings in the earthquake area remained intact, particularly those installed in accordance with latest seismic standards.

However, some sprinkler systems were damaged in the following ways:

- pipes were broken, due to differential building movement or to the sway generated in long pipe runs without adequate bracing
- sprinklers installed in the pendant position from piping above ceilings were in some cases sheared off
- pendant sprinklers installed in drop ceilings were pulled through the ceiling by the upward movement of the pipes, and punched new holes during the downward movement. While punching may not have resulted in leaks, it damaged the sprinkler deflectors (which would have modified the spray pattern) and may have resulted in a significant decrease in sprinkler performance (they would have needed replacement).

Damage to fire alarm systems, smoke control, other extinguishing systems, and to passive building fire protection systems such as fire and smoke barriers, were not reported in the available references.

**Effect of
earthquake on
water supplies**

Todd (1994) reports that whereas fire-fighting water supplies were generally adequate in the San Fernando Valley area during the day of the earthquake the exceptions were in areas near the boundaries of the system and in areas of higher elevation (ie in the western and northern portions of the San Fernando Valley). Santa Monica's water supply system suffered no significant impairment.

EARTHQUAKE SPECTRA (April 1995) reported the damage to the water supply in the San Fernando Valley area :

- breaks in at least six trunk lines
- approximately 3,000 leaks
- pumping stations and storage tanks also sustained damage.

As a consequence, during the hours and days following the earthquake there was a lack of water pressure at the hydrants in much on the western and northern portions of San Fernando Valley. The water shortage had to be made up through the deployment of water tankers and by drafting from alternative sources, including the large number of backyard swimming pools in the area.

On January 20, three days after the earthquake, fire department pumpers were used to pump water from areas of adequate pressure within the system to areas with low pressure.

**Response of the
fire department**

According to EARTHQUAKE SPECTRA (April 1995) at the time of the earthquake the Los Angeles region had a large well-equipped fire service, and sufficient resources were available to deal with all fire ignitions, as well as other emergencies such as Search and Rescue, and hazardous material releases.

Todd (1994) reported that LAFD respond to over 900 fire, medical and other emergencies on a typical day. This number increased to over 2,200 on the day of the earthquake, and during the days following to over 1,800 calls.

In the epicentral area fire-fighting efforts were hampered by lack of water from hydrants, necessitating relay operations and water shuttles to combat the fires and to ensure reserves during the days following, in case fires should break out.

According to EARTHQUAKE SPECTRA (April 1995) experiences of some fire departments following the earthquake revealed potential weaknesses in communications, and some communications systems suffered damage necessitating an altered mode of operation. This caused a significant

impairment to communications within the fire department and degraded emergency response.

Todd (1994) reports that at 6:11am LAFD Operations Control Dispatch (OCD) Centre lost its computer-aided dispatch capability, caused by a mains power outage and the subsequent mal-function of two back-up generators (the engine of the in-service generator set had blown a radiator hose and overheated, and the reserve set failed to take over the load). LAFD then reverted to manual mode dispatch, but restoration of the OCD computer was delayed for a further 7 hours while flooding of the cable space below the computer was cleaned up. This was caused by the activation of a sprinkler by the overheated engine of the generator set.

Emergency 911 calls placed with the fire department were unable to be received by the OCD due to overloaded telephone services public service access point. Additionally, local phone service was lost in some earthquake-affected areas.

Lessons to be learned

Protection of natural gas service lines and appliances

Although the absolute numbers were relatively small, according to Todd (1994) the gas leaks resulting from damage to natural gas pipelines and appliances contributed to a significant fraction of the post-earthquake fires. This would indicate a further study of the impact of earthquakes on building gas service and appliances is warranted, and improved criteria for post-earthquake fire safety of gas service lines and appliances are needed.

Chung (1995) has noted that the technical feasibility of seismically operated shut-offs and control mechanisms should be assessed along with a cost/benefit analyses for the use of these systems. Guidelines for the installation and use of these devices should be developed.

It also suggested that the cost-effectiveness of earthquake-activated electric shutoff switches should be assessed, as these may have some value under at least two potential scenarios:

- major earthquakes can cause local disruptions to electric service, particularly in buildings sustaining serious structural damage. Such disruptions may include faults to ground and short circuits that could act as potential ignition sources. An earthquake-activated electric shutoff switch could deenergise a local electrical system and thereby reduce or eliminate potential ignition sources.
- major earthquakes can cause wide area electric service disruptions. At the same time they can cause the toppling of combustible goods, which may land on electrical appliances, such as ranges, space heaters, and lighting fixtures. This does not pose a risk of ignition as long as electric service is disrupted, but may be hazardous if the electric service is restored before combustibles are removed. An earthquake-activated electric shutoff switch would deenergise a local electrical system and permit a premise to be inspected before the local system is re-energised.

Chung (1995) reported that the above scenario is thought to have been a significant cause of fires following the Kobe earthquake. It noted that while electric shutoff switches may not have been available for seismic applications, shutoff switches activated by movement of objects, noise, or other input were available, and suggested that conversion of the existing technology for seismic applications may not be difficult.

Restoration of utilities after the earthquake

Fires directly attributable to earthquake damage continued to occur in the days following the earthquake, and most of these were caused by the restoration of power to buildings damaged in the earthquake.

Todd (1994) suggested that this issue places at odds the desire to restore utility services as quickly as possible and the desire not to cause additional fires. It suggested that criteria and techniques are needed to allow utility personnel to assess the safety of restoring electricity to damaged buildings. The primary information that should be maintained would be building status, utility system status, and even seismic activity. It suggested state-of-the-art computer-assisted dispatching systems that was being installed by LAFD as possibly providing those means.

Post earthquake fire spread between buildings

Chung (1995) has noted that a significant potential for post-earthquake conflagrations exist in certain areas due to building, landscape, terrain and climatic conditions. The Northridge fire incidents in the three manufactured housing developments are an example. This reference suggests that such areas should be identified as part of pre-earthquake planning, so that appropriate preparations can be made to minimise the potential for conflagrations.

Means of communicating emergencies to authorities

Following the Northridge earthquake there was significant disruption to telephone and other land based communications systems and many citizens were unable to report requests for aid via telephone.

Todd (1994) suggested that this is perhaps one of the most challenging opportunities for reducing the loss of life and property following an earthquake, but noted that even if there had been no damage to communications systems processing the vast quantities of information (needed to make critical decisions) is a significant challenge in itself. It considered the method of locating emergencies by placing public service personnel on patrol and utilizing helicopters, while most likely the best method available at the time, was still inadequate.

This is an area where emerging communications technologies may provide significant improvements.

Water supply line reliability

The need for reliable post-earthquake water supplies for fire protection, and public health, was again demonstrated in the Northridge earthquake when some water systems proved vulnerable to earthquake damage.

Chung (1995) considered an objective should be to enhance the reliability of water supply systems following earthquake and suggested methods of implementation:

- implement seismic design standards and guidelines for existing and new systems
- develop techniques and procedures for rapidly assessing post-earthquake water system damage to assist in emergency response and the isolation of damaged pipelines and water facilities.

Identification and use of alternative water supplies

The Northridge post-earthquake fire-fighting effort depended on the availability of alternative water supplies to deal with fires in many of the earthquake affected areas. This was in common with the experiences from earlier major earthquakes after water distribution systems had been disrupted.

In view of the common reliance placed on them, Chung (1995) considered that jurisdictions should formally identify, critique and document alternative water supply sources and distribution systems. These would include:

- effectiveness of tank trucks (water tenders)
- strategies for water cistern placement
- use of swimming pools and other available stored water sources
- use of fire department pumpers to transfer water between different water systems (eg. high/low pressure) or between parts of the same system
- use of temporary above-ground water mains
- non-potable water sources and delivery systems
- access to untreated municipal water supplies.

Comparisons with other earthquake events

According to EARTHQUAKE SPECTRA (April 1995) there were striking similarities between the 1994 Northridge earthquake and the 1971 San Fernando earthquake:

- two events were of similar magnitude
- affected many of the same locations
- occurred at similar times of day and year
- total number of earthquake-related fires were almost identical
- distribution of fires were quite similar broken gas mains resulted in large flares.

Sekizawa (1997) has compared 1994 Northridge earthquake and the Great Hanshin (Kobe) earthquake. Even though the degrees of damage were different, these two earthquakes under

large modern cities had quite a few similarities, and a significant difference:

- similarities were in terms of the structural damage, disruptions to lifelines, pattern of fire outbreaks, and some barriers to fire-fighting activity, such as damaged fire hydrants
- difference was in terms of the occurrence of conflagrations in city areas: none in Northridge but widespread in Kobe.

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15. The Hyogo-ken Nanbu Earthquake, Japan

The earthquake	Formal name is Hyogo-ken Nanbu earthquake. Also known as: <ul style="list-style-type: none">• the Great Hanshin earthquake, after the Hanshin district where it occurred• “Kobe” which refers to the city most affected by the event .
When. Magnitude. Intensity.	Earthquake occurred at 5.46am, Tuesday 17 January, 1995. According to Chung (1996) it had a Richter magnitude of 7.2. This resulted in a shaking intensity which exceeded MMVIII.
Location of epicentre	This was located about 20km to the southwest of the coastal part of Kobe, just off the north-east end of Awaji Island, at a depth of 16km. Close to the epicentre the approximate values of the peak lateral acceleration was >0.8g, and of the peak vertical acceleration 0.5g.
Area affected	The Hanshin district, which includes the cities of Kobe, Osaka and Kyoto.
Earthquake expectancy	The major seismic activity in Japan, until the Hanshin earthquake, had always been in central and northern Japan. According to NZNSEE (1995) the Kobe area is regarded as having relatively low seismicity for Japan, and the possibility of an earthquake therefore had not been anticipated.
Demographic detail	The Hanshin district has a population of about 15M (approx 15% of the total Japan population).
Geotechnical perspective	<p>According to Chung (1996) most of Kobe is built on a narrow 2 km- to 3 km-wide coastal plain confined between Rokko Mountains and Osaka Bay. From the geotechnical perspective the soils of the coastal plain divide into two major groups, natural soils and man-made landfills. Much of the recent growth of Kobe (ie since about 1953) has been on sandy landfills that were dumped into Osaka Bay onto compressible marine clay.</p> <p>Chung (1996) reports that major reclamations have been undertaken to establish the man-made islands of Port Island (826 ha), and Rokko Island (580 ha) which was completed in 1992. Major settlement has occurred, and is expected to continue for many years. When these artificial fills were subjected to the strong shaking of the earthquake they liquefied and expelled large quantities of both sand and water. Liquefaction was evident over more than 17 km² of land area.</p>
Human toll	Nearly 6,000 people were killed in the earthquake and over 33,000 people were injured. Many were trapped alive in collapsed buildings and killed by the firestorms that followed. Over 500 deaths were caused by fire. The death toll was the greatest caused by an earthquake in Japan since the 1923 Great Kanto earthquake.
Economic loss	According to THE ECONOMIST (1995) the property losses as a result of this earthquake was estimated as 1994 \$US110 billion, making it the costliest earthquake in the world thus far, and its impact has been felt worldwide.
Infra-structure damage	<p>NZNSEE (1995) has reported a narrow zone of severe damage, but widespread damage to underground pipes and elevated transport structures, which can in part be attributed to the extensive soft natural soils and man-made reclamation, and to the urban area being concentrated along a 30km length of fault line.</p> <p>Chung (1996) reports that at the port facilities many commercial piers were destroyed and the liquefaction phenomenon contributed to many of the structural collapses, especially on the artificial islands of Port Island and Rokko Island which suffered major damage.</p>

Damage to structures

FIRE INTERNATIONAL (1995) reported the destruction of over 100,000 buildings, caused by the quake, its aftermath, and the uncontrollable fires that raged about the city.

According to NZNSEE (1995), buildings and bridges designed and constructed according to modern seismic standards in general survived the earthquake well.

However, Chung (1996) reports that in the Nagata Ward (an area that was occupied by more than 69,000 buildings and the worst affected by post-earthquake fires), the buildings were approximately 50 year old predominantly 2 storey wooden structures with heavy ceramic tile roofs. Having insufficient lateral support, the buildings collapsed easily.

Many of these buildings contained residential, commercial, and industrial facilities, frequently intermixed. Many of the industrial occupancies were synthetic shoe factories which worked with highly flammable solvents and plastics. These buildings collapsed into piles of debris that included thin dry wood with large exposed surface areas, and the highly flammable contents.

Fire following earthquake

According to Sekizawa (1997) 89 fires (43%) of all fires on Jan 17 started by 6:00am (14 mins. after the main shock at 5:46am), indicating that the situation can be described as "multiple simultaneous ignitions following an earthquake."

Chung (1996) reports that 205 fires occurred in Kobe and the neighbouring cities of Osaka and Kyoto on the first day. The total number of fires had increased to 240 by midnight four days later (this included 11 very large fires having burned areas greater than 10,000m²). This is supported by Scawthorn & Cowell (1995) who report that on the day of the earthquake about 12 fires in the earthquake affected area developed into conflagrations which burned for about 24 hours, and destroyed about 5000 buildings. The worst affected area was the Nagata Ward where approximately 660,000m² (or 160 acres) of buildings were consumed.

Sekizawa (1997) reported that for Kobe City, only 33% of fires that started by 6:00am on Jan. 17 were single fires which were confined to the structure of fire origin. About 50% of fires by 6:00am spread to be large fires having burned area greater than 1,000m². This indicates that fire brigades could not control post-earthquake fires in their early stage, especially for the fires that started shortly after the earthquake. This situation continued to some extent until midnight Jan 19 in Kobe.

According to Sekizawa, for cities other than Kobe about 73% of fires that started by 6:00am on Jan. 17 were single fires which were confined to the structure of fire origin. About 3% of fires by 6:00am spread to be large fires having burned area greater than 1,000m². The percentage of single fires increased gradually with elapsed time. This indicates that fire brigades functioned fairly well in controlling post-earthquake fires in the regions other than Kobe, even in the period shortly after the earthquake.

NZNSEE (1995) has reported on the general structural severity of the fires that devastated an 18 hectare (45 acres) region of Western Kobe. That estimate was based on the effect of the fire on numerous low- and medium-rise steel framed buildings in the affected area and was assessed as between 15 and 30 minutes time equivalent (the time equivalent is the time under the standard ISO furnace test). However, the occurrence of localised pockets of greater fire severity is reported.

According to NZNSEE (1995), in the medium-rise steel framed buildings in the fire affected zone two general structural steel gravity load-resisting systems

were employed: either unprotected truss beam, or unprotected I-section beams, supporting a light concrete floor on steel deck. The truss beams form of construction suffered considerable damage, typically with collapse of the roof and the upper level and distortion in the lower levels. The I-section beams suffered very little distortion.

The concrete buildings in the fire-affected areas of Western Kobe were of old stock and suffered severe damage in the earthquake. It appears that the subsequent fire did not cause significant further damage to the structural frames.

Timber buildings suffered complete destruction in the earthquake followed by fire. Very little of the timber frames remained, and combustible contents was mostly consumed.

Fire causes

Chung (1996) reports there were several combinations of fuels and ignition sources which most likely caused the fires:

- broken natural gas pipes - these were evident at many of the fire sites of homes and factories, and kerosene heaters were present in the ruins of most of the buildings (the temp. was 3deg.C the morning of the earthquake and some could have been in use at the time)
- power lines - these were either knocked down by the earthquake or torn from collapsed buildings creating potential arcing situations. A significant number of fires started well after the initial shock. These may have been fires associated with aftershocks, or fires resulting from the restoration of electrical power.
- those associated with recovery activities (use of candles in gas affected compartments), fires for warming displaced survivors getting out of control, and fires due to suspected arson.

Sekizawa (1997) considers fires that occurred during the first 14 mins. after the earthquake resulted from gas leakages or gas appliance ignitions, other fire appliances, or chemicals ignition, rather than through "electrical causes". As time elapsed after 6:00am the proportion of gas leakages and gas appliance ignitions, and other fire appliances, or chemicals ignition, decreased, and the proportion of "electrical causes" increased in connection with the recovery of electricity supplies to collapsed structures.

Chung (1996) reports that many damaged homes had a serviceable electric power connection following the earthquake, and suggests that data reported in The Kansai Electric Power Co. report "Earthquake Impact on Electric Facilities of the KEP Co." Feb.2, 1995, supports in part the theory that when electric power was restored damaged appliances, wiring and light fixtures ignited combustibles.

According to NZNSEE (1995) there does not appear to have been close liaison with the gas and electricity suppliers before supplies were restored, and their rapid re-instatement was a significant cause of fresh ignitions. That restoration of electricity was very rapid is indicated by the following time-line:

- two hours after the earthquake about 1 million customers were without power (out of 11.7 million customers supplied by the company)
- within 8 hours supply was restored to 50% of these
- within 3 days to 90%.

Within 5 days supplies were restored to virtually all customers requiring power.

Fire spread mechanisms

Chung (1996) has described the three primary means of fire spread in conflagrations:

- flame spread over a continuous fuel surface or array ie. direct flame impingement on the fuel
- ignition of adjacent fuel by thermal radiation from flames

- spot ignitions started down wind of the main fire by burning brands and embers.

For fire to spread by flame impingement the flames must spread along a continuous fuel chain. These continuous fuel chains eg. piles of rubble, were prevalent in earthquake damaged areas. Buildings collapsed and in some cases across streets, leaving combustible debris next to adjacent buildings and providing a path for fire spread between buildings, and from one block to another.

Chung (1996) also identified automobiles as a mechanism for fire spread. Burnt automobiles were seen in narrow alleys between burnt buildings. Serving as a source of fuel they helped to spread fire from one building to another. Parking areas with burnt cars were also observed. Without the fuel provided by the automobiles the parking areas would have acted as fire breaks.

For fire to spread solely due to thermal radiation the "source fire" must be intense enough to heat the target fuel, which is remote from the fire, to its spontaneous ignition temperature (for many organic materials this is approx. 600 °C (Drysdale, 1985). According to Chung (1996) the heat release rate of a collapsed wooden structure is less than that of the structure prior to collapse, due to under-ventilated conditions. The intensity of fires was reduced since a large number of combustible buildings in the fire area collapsed. The reduced "source fire" intensities of the collapsed structures therefore minimised the flame spread by radiation. Wire glass exterior windows also appeared to be effective in reducing the fire spread. These windows with small gauge wire are common in Japan.

Chung (1996) has reported that for fire to spread due to burning brands or embers, brands must be lofted into the air by the fire, be blown by the wind and land on unburned fuel. If they are hot enough when they land on the fuel to provide ignition, the fire spreads. However, due to favourable weather conditions the wind did not lead to "branding" to any significant extent.

Weather data from the Meteorological Research Institute (Japan), Jan.1995, gave the average wind velocity during the 3 days following the earthquake as low (on 17 Jan: 2.6 m/s; on 18 Jan. 3.6 m/s; on 19 Jan. 3 m/s). According to Todd (1994) experience and predictions of fire conflagrations indicate that at wind speeds above 9 m/s the fire spread and loss will increase dramatically due to flame extension and direct flame impingement. According to Chung (1996) the spread of fires was relatively slow.

Damage to fire safety systems

According to Chung (1996) active building systems were not a factor in mitigating the fires during this disaster:

- no active systems were present in the residential fire areas and only hose stations and stand pipes were observed in the burned out industrial / commercial areas.
- a few hose station systems (in buildings) had self contained water supplies. However the majority of suppression systems were rendered useless by a lack of water due to the broken supply piping
- even if the fire department could have supplied water to the standpipe systems of a building, many standpipe connections were observed to have broken free of the building system.

Some passive systems were effective in stopping the fire's spread or limiting fire damage to the exterior of the building. These structures included:

- schools which had perimeter walls and open spaces around the buildings serving as playgrounds and sportsfields. Although they also had many unprotected openings, such as large windows and doorways, the surrounding spaces in conjunction with the perimeter walls served to

prevent fire spread.

- electric power sub-stations ("bunker style" concrete construction and no windows) also had perimeter walls typically 2m or less in height which served to prevent fire from encroaching on the building. Even though the flame impinged on the exterior walls, the buildings did not ignite.
- gasoline stations are required to have concrete block perimeter walls, approx. 2m tall with non-combustible shielding around the top (intended to protect adjacent structures from a fire at the station) After the earthquake, these walls protected the station from fire in the adjacent buildings.

Chung (1996) reports that most of the structures involved in the post-earthquake fires were old two-storey, wooden framed structures with a mortar exterior similar to stucco which, although non-combustible, dislodged during the earthquake. Those buildings which did not collapse had their wood lattice and bamboo construction exposed, providing an optimized burning configuration. This was well ventilated, of extensive surface area, and layered to allow re-radiation.

Many buildings with non-combustible exteriors were destroyed by fire because flames from surrounding burning buildings penetrated openings such as windows. Other buildings with non-combustible exteriors had wired glass in their windows. Although they would crack from the heat of the flame, the wire kept the glass in place and did not allow the flame to penetrate to the inside of the building. Steel shutters also provided successful window and door protection.

Clusters or groups of fire resistive buildings, with noncombustible exteriors served to prevent the spread of fire. If the fire resistive buildings were surrounded by combustible structures, a fire starting in the combustible structures would burn around and in some cases through the fire resistive building. Fire spread from one fire resistive building to another was not evident.

Effect of earthquake on water supplies

Scawthorn & Cowell (1995) reported that fire water was primarily from the city water system served by gravity from 30 reservoirs. Of these, 22 had dual tanks with one tank of each pair having a seismic shut-off valve to conserve its contents for fire fighting in the event of an earthquake. In response to this earthquake all 22 valves functioned properly, conserving 30,000m³ of water.

There were approx. 23,500 fire hydrants, typically flush-mounted (under a steel plate in the footpath or roadway) with one 150mm hose connection. Although many of the hydrants were found inaccessible due to collapsed buildings and debris most of them were dry because of approximately 2,000 breaks in the underground piping water.

Chung (1996) reported that Kobe had made significant preparation for a loss of the fire hydrant system by constructing 971 water cisterns across Kobe City for fire fighting use. Capacities ranged from 10,000 to 40,000 litres (Scawthorn reported the latter to be a 10 minute supply for a pumper). Although 628 cisterns were reinforced to withstand earthquakes, of the 92 in the Nagata Ward (where fire damage was most severe) only 23 were seismically reinforced. Given the extent of the ground motion it is likely that many of the older cisterns were damaged and lost their water. The cisterns were also intended for emergency domestic use. The need to use this water for fire-fighting resulted in a critical shortage of drinking water later in the incident.

According to FIRE CHIEF (1995) in addition to the cisterns, other water sources had to be used to fight the advancing fires. Water was also drawn from swimming pools, a river and the ocean. Pumps were used in tandem (typically six) to pump water from its source to a fire. However, due to friction

loss only two hose lines at a time could be deployed by the last pumper. Fighting fires in this manner proved to be extremely labour and equipment intensive.

Chung (1996) reported that tankers were used to ferry water to fire locations. However, streets which were still negotiable were also congested with pedestrian and vehicle traffic. To enable them to navigate the narrow streets fire apparatus in Japan are small, and this limits the amount of water the trucks can carry (approx 800l), and with the difficulty of obtaining water at the fire sites, these trucks had to be used to transport water. This was a slow and difficult process given the congestion and debris on roads.

Scawthorn & Cowell (1995) reported that the Kobe Fire Department (KFD) attempted to supply water with a fireboat and relay system, but this was unsuccessful due to the relatively small hose used by the KFD.

Scawthorn described his flight over the area at about 5:00PM on January 17. He was able to observe all of the (8) larger fires from an altitude of less than 300m. No fire hose streams were observed. All fires were burning freely (several with flames 6m or more in height). No fire apparatus could be seen in the vicinity of the large fires, although fire apparatus could be seen at other locations (their activities were unclear from the air).

Water for fire-fighting purposes was available for only 2 to 3 hours. Some residents formed bucket brigades and used sewer water to try to control the flames.

Response of the fire department

Sekizawa (1997) described several factors which define the possibility for major fire spread (or conflagration) following an earthquake as:

- the extent that fire-fighting activity is successful at an early stage of fire outbreak (ie. the performance of the fire-fighting activity). In this earthquake, he considered this to be a key factor to the differences in fire damage in the various earthquake affected regions.
- the higher risks of fire spread due to particular urban configuration aspects, such as inadequate fire-resistive construction in buildings, insufficient separation between structures, and narrow streets

Success of fire-fighting activities is influenced by fire department resource aspects, (eg. availability of fire-fighting water, availability of equipment appropriate to the fire challenge), fire department access to the fire site and fire fighter intervention at the earliest possible stage of fire development.

As an indicator of average fire size, and the degree of success of the fire-fighting efforts, Sekizawa has assessed values for the average number of burned structures per fire. Osaka and Kyoto had less than 2.5, and Kobe's less damaged regions (like Tarumi ward, Kita ward, and Nishi ward) had less than 2.0 burned structures per fire. According to Sekizawa these facts indicate that most of the post-earthquake fires were suppressed in their early stage by fire brigades, especially in cities other than Kobe. Lower average fire size was due to fire-fighting performance. The concentration of large fires around Nagata ward was not simply because of the high incidence of fires, but also because of the higher risks of fire spread attributed to city configuration (ie ratio of wooden structures and average distance between adjacent buildings).

FIRE CHIEF (1995) reported that although Kobe has a state-of-the-art command and control centre, it was unable to function as intended in the critical minutes after the earthquake (despatchers were unable to receive any incoming emergency telephone calls due to major damage to the telephone equipment and call over-loading). As a result of this communications breakdown, control of operations in each area of the city was transferred to the

fire stations (as stipulated in their disaster plan).

Chung (1996) reported that the Kobe City Fire Bureau is a modern and relatively well manned, and well trained and equipped fire brigade (27 stations, more than 200 vehicles, and approx. 1300 regular staff and 4000 volunteer corp members). However, in Kobe the fire service had very limited success in containing or suppressing the fires. The difficulties faced were multiple fires across the city at one time, limited water supply, limited access to fire sites, impaired communications and earthquake damage affecting the fire stations and fire fighters.

Chung (1996) provides a basis for comparison: in 1992 Kobe City Fire Department responded to 812 reported calls (Statistical Data of the Kobe City Fire Bureau, Kobe Japan, April 1993). Over a typical four day period they would expect to respond to nine reported calls or approx. two per day. Immediately following the earthquake 53 fires were reported (almost two fires per station), but they were not uniformly distributed (they were concentrated on the east and west sides), and many of these initial fires were fed by natural gas and grew quickly. No fire department is prepared to immediately handle that number of major fire incidents simultaneously.

This was confirmed by Sekizawa (1997):

- in Kobe fire brigades could not control post-earthquake fires in their early stages of growth, especially for the fires that started shortly after the earthquake. A backlog of unsuppressed fires added to their burden and greatly influenced the extent of fire damage in that region. This situation continued to some extent until midnight Jan 19 in Kobe.
- for cities other than Kobe fire brigades functioned fairly well in controlling post-earthquake fires, even in the period shortly after the earthquake, and the fire brigades could cope with sequential fires.

Sekizawa suggested that given a secure water supply the extent of post-earthquake fire damage depends basically on the balance of the number of simultaneous fires and the fire-fighting resources (ie. fire engines) available for despatch.

FIRE CHIEF (1995) reported that the larger fires could not be controlled until they reached greenbelts or major arterial highways. The area hit hardest was Nagata Ward, which experienced an initial outbreak of 13 structure fires. Fire-fighters were over-whelmed. Some of the fires burned totally out of control because resources were not available to fight them. The fires in Nagata Ward and other sections of Kobe raged for two days, burning large tracts of housing, retail stores and factories. The desire of fire-fighters to rescue people was pre-empted by the need to take a stand against uncontrolled fires which threatened the entire city.

Chung (1996) reported on the use of models for the optimisation of post earthquake fire fighting efforts which predict simultaneous ignitions and the rate at which the fires are spreading, and compare them with the fire service response times and suppression effectiveness. These models are beneficial for pre-planning but they assume that the fire department can access the fire site and that water for fire fighting will be available. In Kobe accessibility and water were the exception.

Lessons to be learned

Water supplies

According to NZNSEE (1995) the principle lesson for NZ is the impracticability of stopping fire spread without water, given that reticulated water supplies are likely to be disrupted.

Chung (1996) considers that recent earthquakes have shown there is a low probability of maintaining a water system following an earthquake, and recommends that water supply utilities and fire departments should re-look at the vulnerability of water supplies. An objective would be to increase the probability of delivering water to suppress fire. Consideration should be given to identifying and developing alternate supplies:

- one such system might consist of caches of high volume, diesel powered (or other independent power supply), portable pumps located near natural sources of water around the city.
- another is the use of aircraft for fire-fighting. Although aircraft dropped water cannot attack interior fires it may be effective on fires in rubble. Also, fire fighting from the air may be a method of overcoming the problem of accessing the fires due to blocked roads.

FIRE INTERNATIONAL (1995) reported that helicopters were not used for fire-fighting in Kobe, but for airlift rescue operations and reconnaissance. Dropping large quantities of water from an altitude of 70 to 80 metres could have killed people trapped under debris in wrecked buildings. Also, high rise buildings and unstable air currents due to fires would have made it hard for the helicopters to maintain definite altitudes over urban areas on fire.

Control over the re-instatement of electricity and gas supplies as a means of limiting ignitions

Chung (1996) reported means of limiting ignitions:

- re-energisation of an earthquake damaged area needs to be coordinated between the different utilities and the emergency rescue and recovery services. Work needs to be conducted on the impact of earthquakes on gas service to buildings and appliances.
- prior to restoration of electrical service, techniques or instrumentation needs to be developed to ensure that electricity is not restored to damaged structures or areas with natural gas leaks.

Need for passive fire protection systems on a city-wide basis

Chung (1996) considered that passive fire protection systems need to be designed on a city wide basis:

- a network of wide roadways (ie. fire resistive egress corridors for cities) would serve as fire breaks and provide ample egress and emergency access.
- consideration must be given to buildings which border the egress route. They should not only be designed to withstand earthquake forces but should also be built of non- combustible materials.
- there is a need to examine current construction requirements for fire resistive buildings, especially the protection of openings such as windows and doorways. Special efforts should be taken toward materials or systems which could be retrofitted to existing structures.

Need for aggressive attack strategies against fire in urban areas

Fire spread rapidly through the closely spaced wooden houses.

According to Sekizawa (1997) the Hanshin earthquake left Japan with the significant task of how to improve means of fire spread prevention in city areas with zones having very packed wooded structures.

NZNSSE (1995) considered that in NZ aggressive fire attack strategies also need to be developed for those areas of urban development that are at risk from radiated heat transfer due to housing being constructed close together, or a combination of radiated and convected heat transfer due to housing being sited vertically close together in steep hill suburbs.

In terms of urban conflagration risk, the built-up areas most at risk from widespread fire are the suburbs. The commercial business districts are likely to be least at risk, and the risks in industrial districts depend on the industry.

According to NZNSEE (1995) reinforced concrete and steel framed multi-storey buildings are likely to exhibit good post-earthquake stability under fire attack, but fire will spread through such buildings unless active suppression systems remain operational after the earthquake.

FIRE CHIEF (1995) considered the extreme importance of controlling the initial outbreak of fire, especially in areas that are prone to a conflagration risk. Although fire-fighters are trained to place rescue activity on a higher level of priority than structural fire-fighting, experiences in Kobe suggest that the opposite may be true following a major quake when most of the citizens in major buildings who could be rescued were able to rescue themselves. Rescue for the remainder of trapped victims would generally prove to be a laborious, time-consuming operation.

END OF APPENDIX 2

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FIRE ENGINEERING RESEARCH REPORTS

95/1	Full Residential Scale Backdraft	I B Bolliger
95/2	A Study of Full Scale Room Fire Experiments	P A Enright
95/3	Design of Load-bearing Light Steel Frame Walls for Fire Resistance	J T Gerlich
95/4	Full Scale Limited Ventilation Fire Experiments	D J Millar
95/5	An Analysis of Domestic Sprinkler Systems for Use in New Zealand	F Rahmanian
96/1	The Influence of Non-Uniform Electric Fields on Combustion Processes	M A Belsham
96/2	Mixing in Fire Induced Doorway Flows	J M Clements
96/3	Fire Design of Single Storey Industrial Buildings	B W Cosgrove
96/4	Modelling Smoke Flow Using Computational Fluid Dynamics	T N Kardos
96/5	Under-Ventilated Compartment Fires - A Precursor to Smoke Explosions	A R Parkes
96/6	An Investigation of the Effects of Sprinklers on Compartment Fires	M W Radford
97/1	Sprinkler Trade Off Clauses in the Approved Documents	G J Barnes
97/2	Risk Ranking of Buildings for Life Safety	J W Boyes
97/3	Improving the Waking Effectiveness of Fire Alarms in Residential Areas	T Grace
97/4	Study of Evacuation Movement through Different Building Components	P Holmberg
97/5	Domestic Fire Hazard in New Zealand	KDJ Irwin
97/6	An Appraisal of Existing Room-Corner Fire Models	D C Robertson
97/7	Fire Resistance of Light Timber Framed Walls and Floors	G C Thomas
97/8	Uncertainty Analysis of Zone Fire Models	A M Walker
97/9	New Zealand Building Regulations Five Years Later	T M Pastore
98/1	The Impact of Post-Earthquake Fire on the Built Urban Environment	R Botting
98/2	Full Scale Testing of Fire Suppression Agents on Unshielded Fires	M J Dunn
98/3	Full Scale Testing of Fire Suppression Agents on Shielded Fires	N Gravestock
98/4	Predicting Ignition Time Under Transient Heat Flux Using Results from Constant Flux Experiments	A Henderson
98/5	Comparison Studies of Zone and CFD Fire Simulations	A Lovatt
98/6	Bench Scale Testing of Light Timber Frame Walls	P Olsson
98/7	Exploratory Salt Water Experiments of Balcony Spill Plume Using Laser Induced Fluorescence Technique	E Y Yii

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